SCIENCE ENVIRONMENT SOLUTIONS

Cooperative Institute for Atmospheric Sciences and Terrestrial Applications (CIASTA)

ANNUAL REPORT
NOAA Cooperative Agreement NA17RJ1222
July 1, 2002 – June 30, 2003

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TABLE OF CONTENTS

ANNUAL PERFORMANCE REPORT
JULY 1, 2002 TO JUNE 30, 2003

I. CIASTA Mission

The Cooperative Institute for Atmospheric Sciences and Terrestrial Applications was formalized with the signing of a Memorandum of Understanding between the National Oceanic and Atmospheric Administration (NOAA) (Administrator D. James Baker, signatory), represented by the Office of Oceanic and Atmospheric Research, the National Weather Service, and the National Environmental Satellite, Data, and Information Service and the University and Community College System of Nevada (Chancellor Richard S. Jarvis, signatory), represented by the Desert Research Institute (DRI).

The CIASTA will carry out a number of activities, including, but not limited to:

- Foster long-term collaborative research on themes of mutual interest.

- Facilitate the establishment of joint research projects between scientists of NOAA and universities in the Intermountain West (Rocky Mountains to the Sierra Nevada/Cascade Mountains).

- Improve the effectiveness of graduate-level education and expand the scientific experiences available to graduate students to include their participation in joint research programs with NOAA.

- Serve as a focal point for the interaction between NOAA and the Intermountain West research community for research activities related to NOAA's tasks and responsibilities in that region.

- Provide the mechanism to develop a major, multi-sponsor program for the Intermountain West in weather research, climate research and services, air quality research, and terrestrial studies.

The work of the CIASTA is organized into five tasks:

Task 1. Administration and Visiting Fellows Program

Task 11. Weather Research

Task 111. Climate Research and Services

Task IV. Air Quality Research

Task V. Terrestrial Ecosystems and Climate

II. CIASTA Activities

New CIASTA Director: After a nationwide search, Dr. Mark Green was selected as CIASTA Director, effective April 1, 2003. Dr. Green is a Research Professor in DRI's Division of Atmospheric Sciences at the Southern Nevada Science Center in Las Vegas and has been with DRI since October 1990. His research has focused on identifying the causes of visibility degradation. His CIASTA projects have included the Project MOHAVE and BRAVO regional visibility studies. Dr. Green received a BS in Atmospheric and Oceanic Sciences from the University of Michigan, an MS in Meteorology from the University of Utah, and a PhD in Atmospheric Sciences from the University of California at Davis.

For the period July 1, 2002 through March 31, 2003, Dr. Richard Reinhardt continued in the position of Acting Director for CIASTA.

Meetings:

February 12, 2003
NOAA Joint Institute Directors' Meeting
Annual AMS Meeting, Long Beach, CA

III. Research Reports

TASK II: WEATHER RESEARCH

Monitoring of Coastal Precipitation with the WSR-88D during CALJET

Project Personnel: David Kingsmill (DRI/DAS)
Task: Weather Research
Goal: Use radar data to better characterize precipitation processes in storm systems making landfall on the California coast.

The objective of this project during the reporting period has been to use WSR-88D radar data along with other datasets collected during the 1998 California Landfalling Jets experiment (CALJET) to better characterize precipitation processes in storm systems making landfall on the California coast. The primary activity has been analysis of data from a vertically pointing Doppler radar deployed at Cazadero (CZD) a site in the coastal mountains north of San Francisco. The ten largest precipitation events in terms of storm total accumulation over the January-March 1998 period were examined. Precipitation processes for each case were compared against each other, with significant differences apparent. Some of the differences can be explained from variations in the synoptic regimes associated with each case. However, there were several instances where the same synoptic regime in different cases produced radically different precipitation structures. Radar data at CZD were also compared with WSR-88D data to address variations in precipitation processes at a different site in the coastal mountains (KMUX) and at a site in the Sacramento valley (KDAX). There were clear differences in precipitation structure between CZD and KDAX and even some evidence of differences between CZD and KMUX.

In addition to these activities, the PI has been involved in several collaborative studies with Marty Ralph, Allen White, Paul Neiman and Ola Persson of the NOAA Environmental Technology Laboratory (ETL). These studies, all using data from the 1998 CALJET experiment, include analysis of a flooding event in the Santa Cruz mountains, a seasonal investigation of intense coastal precipitation occurring with shallow clouds and no bright band and an examination of frontal modification by coastal orography in southern California.

The following project related publications have appeared or been submitted during the reporting period:

Kingsmill, D. E., P. J. Neiman, F. M. Ralph and A. B. White, 2003: Synoptic and topographic variability of northern California precipitation characteristics in landfalling winter storms observed during CALJET. Preprints, *5th Conference on Coastal Atmospheric and Oceanic Prediction and Processes*. Seattle, Amer. Meteor. Soc., 183-189.

Neiman, P. J., P. O. G. Persson, F. M. Ralph, D. P. Jorgensen, A. B. White and D. E. Kingsmill, 2003: Modification of fronts and precipitation by coastal blocking during an intense landfalling winter storm in southern California: Observations during CALJET. *Mon. Wea. Rev.* In press.

Ralph, F. M., P. J. Neiman, D. E. Kingsmill, P. O. G. Persson, A. B. White, E. T. Strem, E. D. Andrews, and R. C. Antweiler, 2003: The impact of a prominent rain shadow on flooding in California's Santa Cruz mountains: A CALJET case study and sensitivity to the ENSO cycle. *J. Hydrometeor.*, In press.

White, A. B., P. J. Neiman, F. M. Ralph, D. E. Kingsmill and P. O. G. Persson, 2003: Coastal orographic rainfall processes observed by radar during the California Land-falling Jets experiment. *J. Hydrometeor*, **4**, 264-282.

Improvement of WSR-88D Quantitative Precipitation Estimates (QPE) in the Intermountain West

Project Personnel: Arlen Huggins; David Kingsmill; David Mitchell; Morien Roberts; T. Sam Keck; Kevin Keating; Huaqing Cai (DRI/DAS)

Task: Weather Research

Goal: Improve short-term forecasts and warnings related to summer convection and winter storms in the intermountain West

1. Introduction

The overall goal of this project is the improvement of QPE in the inter-mountain West for the purpose of improving short-term forecasts and warnings related to summer convection (flash floods) and winter storms (heavy snowfall and floods). The project has four main objectives: 1) to develop an algorithm based on the vertical profile of reflectivity (VPR) to correct for the effects of range and the bright band, 2) to develop a means of detecting inhomogeneous radar patterns and reducing errors introduced by the application of inappropriate Z-R relationships or range corrections, 3) to develop an algorithm that extends the VPR below the lowest radar sampling level using the output of a snow growth model, and 4) to make products from the algorithm available in real time to forecasters in the Reno NWSFO. In this the final year of the project significant progress has been made in accomplishing these objectives. This report summarizes the results of work related to each main objective.

2. Creation and use of the WSR-88D VPR for range correction

As pointed out in numerous prior studies, including Andrieu and Creutin (1995), Seo et al. (2000) and Joss and Lee (1995), radar VPR, even ones based on climatological averages, can be used to adjust radar measurements taken at long range (high altitude) to a level near the surface and thus make either measurements of reflectivity factor (dBZ) or rainfall rate (R) more realistic. Some schemes convert profiles of dBZ to profiles of R, then adjust R downward to the surface. The scheme developed in this CSTAR work uses the slope of the VPR to adjust dBZ downward to a level closer to the surface, then applies the Z-R relationship to the adjusted dBZ value. The Z-R relationship used here was also derived from empirical gauge-radar comparisons using VPR-adjusted Z values.

This CSTAR algorithm work was done in one of the more challenging regions of the U.S. for deriving quantitative precipitation estimates (QPE) from radar measurements, a mountainous area which included a part the Sierra Nevada and numerous ranges in the Great Basin. The specific radar chosen was the Reno WSR-88D (KRGX) which, at 2.54 km altitude, is one of the highest

NWS radars in the U.S. During winter, at ranges beyond about 50 km, the lowest tilt from KRGX nearly always samples above the freezing level. In summer the radar frequently samples well below the bases of the common high-based thunderstorms of the inter-mountain West.

One of the key findings in studies of the past three years was that VPR's developed from KRGX volume scans were highly terrain dependent. Thus one VPR, developed from data averaged over the entire coverage area, was found to be inappropriate for regions where precipitation was orographically enhanced, or for areas where precipitation was reduced by downslope flow. For this reason VPR's were constructed over specific regions where terrain-induced effects were relatively consistent. An example of the variation in VPR is shown in Fig. 1where the VPR furthest to the left was created in a region downwind of the Sierra Nevada and the VPR furthest to the right was created in the orographically enhanced region of the Sierra Nevada.

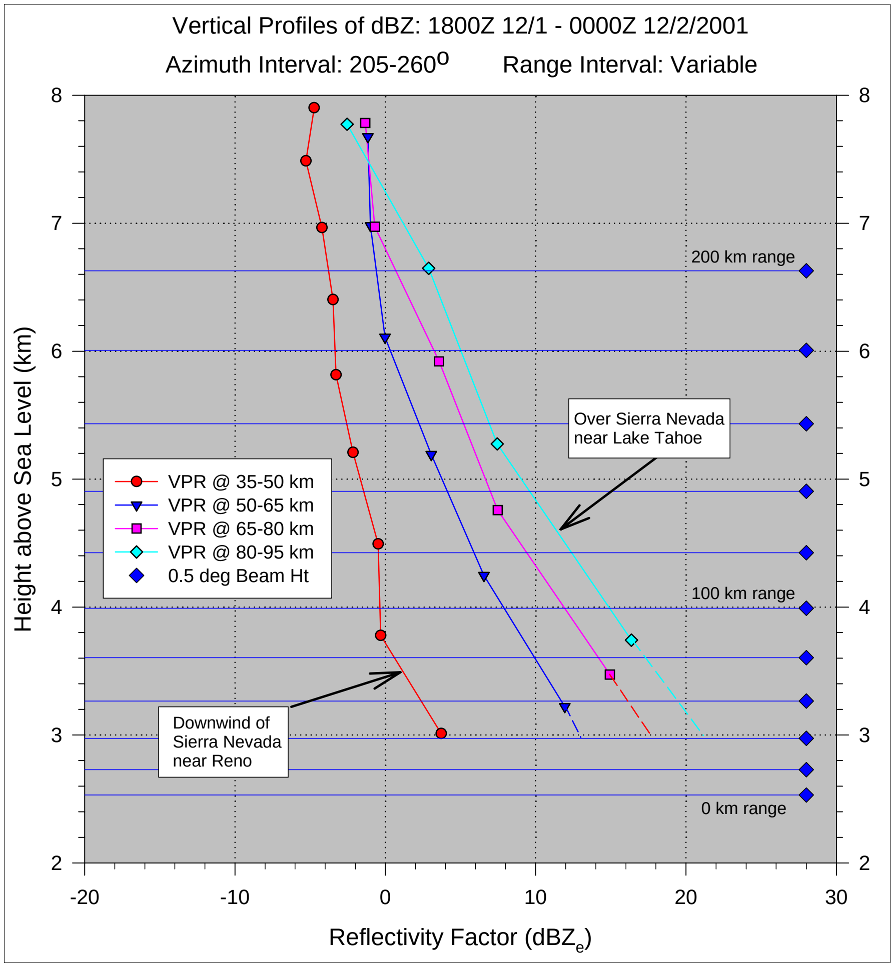

Figure 1. Vertical profiles of reflectivity (VPR) constructed to the southwest of KRGX at four different range intervals. The orographic influence of the Sierra Nevada is seen in the progression from left to right, where the profile on the left is downwind of the Sierra Nevada and the profile on the right is over the mountains near Lake Tahoe. To estimate precipitation the VPR are projected down to the same height level (dashed lines) before a Z-R relationship is applied.

The latest version of the VPR scheme uses profiles over the eight areas shown in Fig. 2. Regions 1 and 2 are centered over the higher terrain of the Sierra Nevada in a range increment where there is typically sufficient cloud depth for developing VPR from two or more elevation tilts. Region 3 is further to the west (generally upwind) where orographic enhancement of precipitation is greatest, and Region 4 is even further west where orographic enhancement from the Sierra Nevada begins. Since the second tilt from KRGX is above 6 km in Regions 3 and 4, VPR's cannot consistently be constructed in winter storms. The profiles in these areas are therefore created by increasing the slope of the Region 1 VPR (cyan VPR in Fig. 1) for Region 3, and decreasing the Region 1 slope for Region 4. The final slope adjustments were determined after numerous winter cases were studied, in which the slopes were adjusted incrementally to obtain the best agreement with precipitation measurements in Regions 3 and 4. Regions 5-8 are in the four radar quadrants east (generally downwind) of the Sierra Nevada. Once a VPR is determined for each region, a smoothing routine is run to lessen the discontinuity found at the boundaries of the eight regions and a correction value (in dBZ) is found for each range bin in the coverage area.

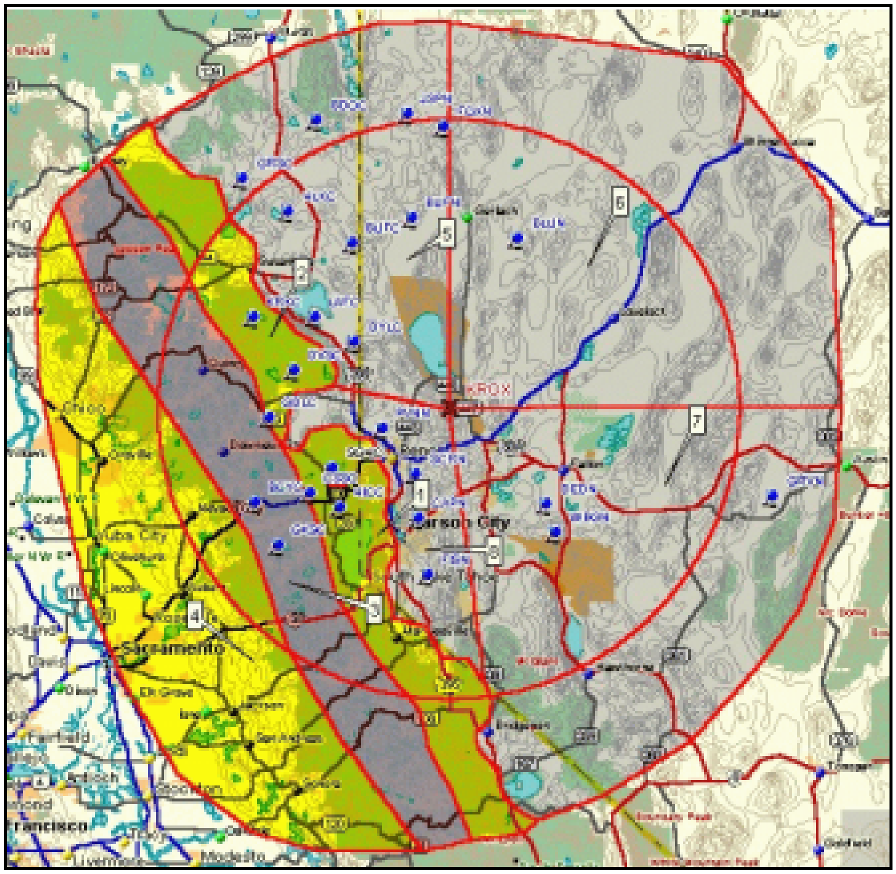

Figure 2. Map showing the KRGX coverage area and the eight regions (shaded and numbered) where different VPR's are created. The inner red circle is the 150 km range ring which is the outer limit for algorithm QPE computations during the winter season. Blue pins show the locations of some of the precipitation gauge sites used in QPE verification.

The VPR scheme in the CSTAR precipitation algorithm was tested and modified during two winter seasons (2001-02 and 2002-03) and showed a significant improvement in wintertime QPE compared to results obtained from the standard NWS Precipitation Processing Subsystem (Fulton et al., 1998). A comparison of storm total radar QPE and precipitation gauge storm totals, for four sites in the Sierra Nevada, is shown in Fig. 3 for 37 storm periods between December 2002 and April 2003. For this study the VPR in the eight regions were averages compiled from about 200 storm periods of 1.5 to 3.0 hour duration from the 2000-01 and 2001-02 winter seasons. The overall radar-gauge correlation (R^2) was 0.83 with the best correlation being at the Central Sierra Snow Lab (R^2 = 0.96) and the worst being at Blue Canyon (R^2 = 0.80). The poorer correlation at Blue Canyon was not surprising since the KRGX 0.5° beam center is at a height of 4.4 km MSL, about 2.8 km above the gauge site. Partial beam filling and total overshooting of shallow clouds at the range of Blue Canyon is not uncommon during some portion of nearly every winter storm. This should lead to precipitation underestimation. However, it appears that the VPR correction did very well in about half the cases, but produced a gauge-to-radar bias less than one for the other cases. This indicates the average VPR correction at the west side of Region 3 was apparently too drastic in about half the storms, suggesting the over-correction more than compensated for periods when beam filling or overshooting was a problem.

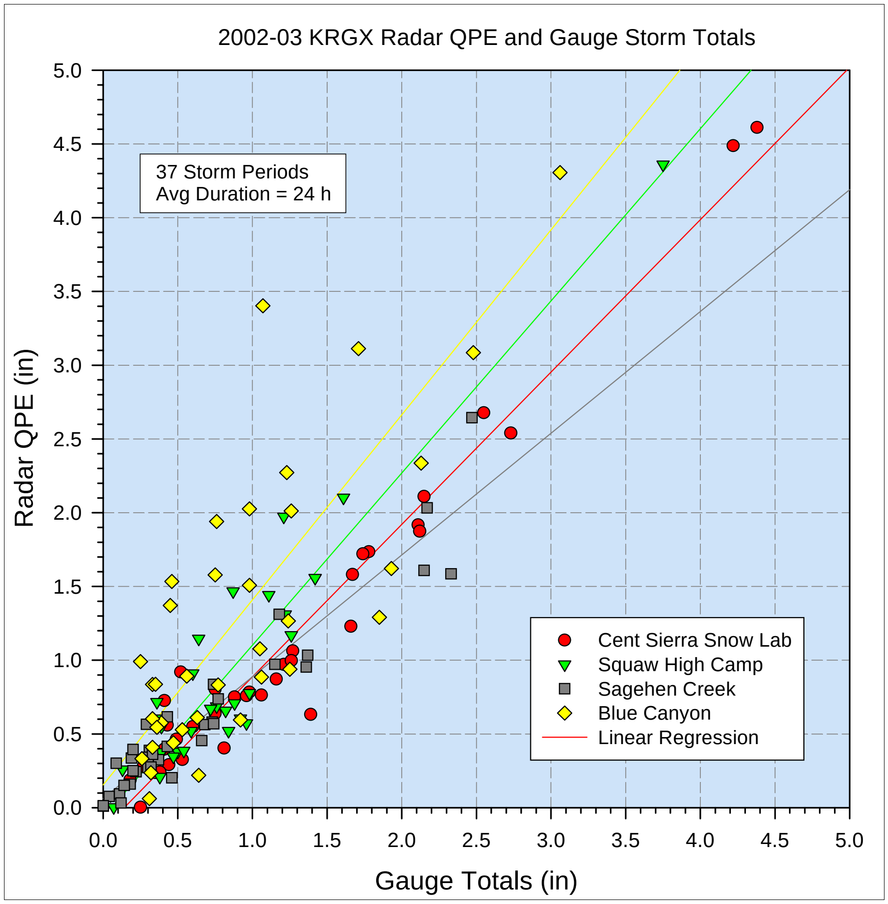

Figure 3. Comparison of storm total radar-derived QPE from the CSTAR algorithm and gauge accumulations at four sites in the Sierra Nevada. Squaw High Camp (green triangles) and Sagehen Creek (gray squares) are in Region 1 of Fig.2, Central Sierra Snow Lab (red circles) is near the boundary of Regions 1 and 3, and Blue Canyon (yellow diamonds) is furthest west near the boundary of Regions 3 and 4. Linear regressions are shown for each set of data.

The development of the VPR correction method has satisfied the bulk of Objective 1. The use of the VPR for bright band correction was studied by Hennings (2000), but its inclusion in the CSTAR precipitation algorithm was not completed, primarily because of the very infrequent observation of the bright band by the KRGX WSR-88D. The multi-partition VPR method has also lead to a means of accomplishing Objective 2 since the use of different VPR's for different areas accounts for differences in echo structure over the coverage area. At present, due to results obtained early in the project (Huggins and Kingsmill, 1999), two different Z-R relationships are also applied, one for regions 1-4 in Fig. 2 and one for regions 5-8. This too accounts for differences in cloud and precipitation particle types. The final version of the algorithm will have criteria, based on the VPR parameters from the previous one to three hours, which will change the VPR and Z-R (if needed) in real time.

3. Use of a Snow Growth Model to adjust the VPR below the KRGX sampling level

Prior CSTAR and CIASTA reports have described a Snow Growth Model (SGM) developed by Mitchell (1988) and revised for use in the CSTAR project. The model is initiated by sounding

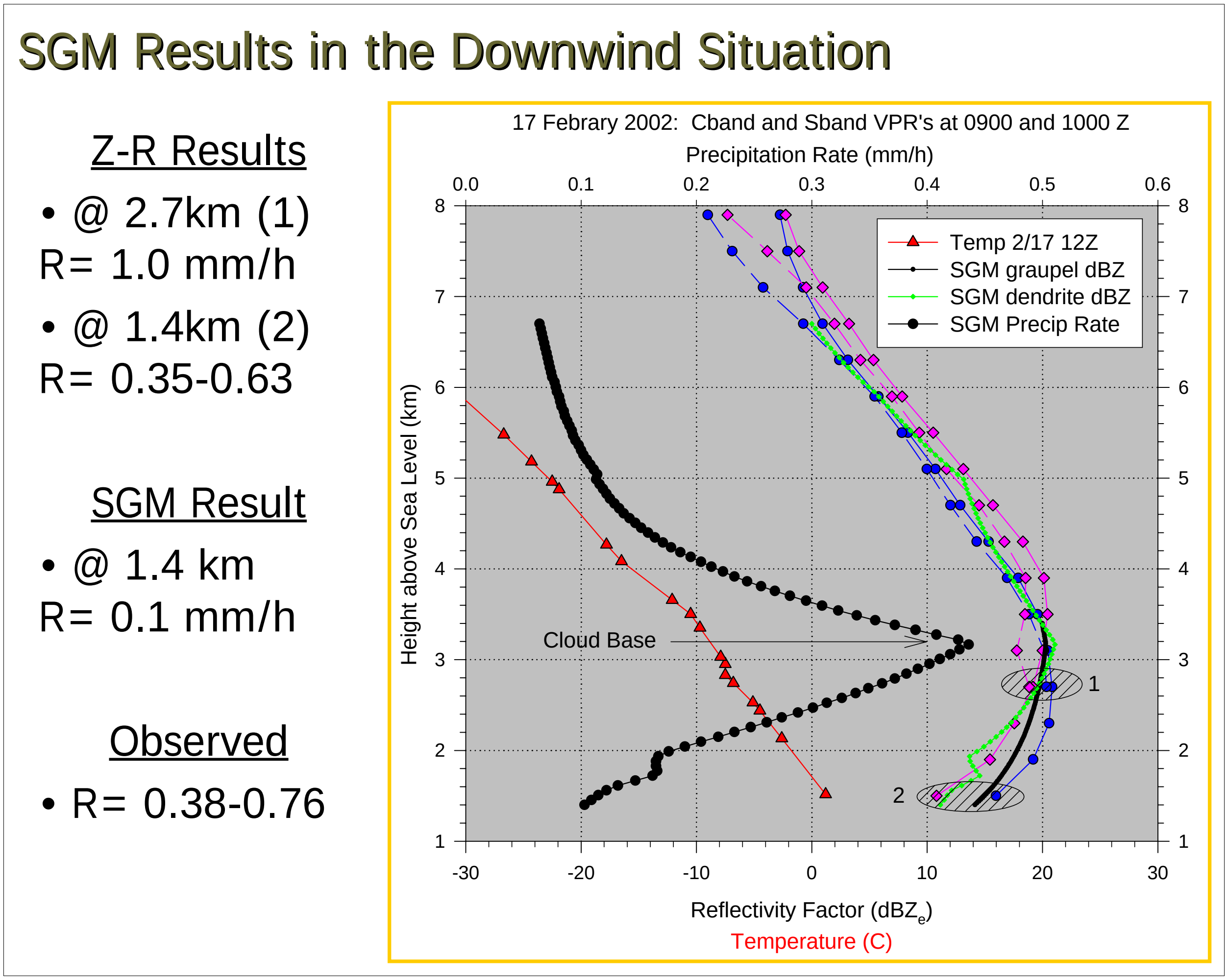

Figure 4. One-hour average C-band and S-band VPR's at two time periods on 17 February 2002 (pink and blue lines and symbols). S-band profiles terminate at about 2.7 km and C-band profiles at about 1.5 km MSL. SGM profiles for dendritic particles (green line) and graupel particles (black line) are also shown. Precipitation rates determined from the Z-R relationship, $Z = 100R^2$, are shown to the left of the figure for Z at the base of the S-band profile (hatched area 1) and C-band profile (hatched area 2). The SGM-predicted precipitation rate profile is shown by the black line and circles.

temperature, which governs ice particle type, and humidity, which affects particle growth and evaporation, and the radar VPR. An observation or estimation of cloud base height is also required. Theoretical and empirical relationships are used to convert the VPR to a profile of ice water content (IWC), develop a size distribution of ice particles from the IWC, grow the particles by vapor deposition and/or riming as they descend, and predict the final particle size distribution at some point below the radar sampling level. The final size distribution is then converted back to a radar reflectivity factor in dBZ and the Z-R relationship is applied to this adjusted dBZ value.

In 2001-02 a C-band radar was operated by DRI at a site about 1.2 km below the altitude of KRGX. Volume scan data from this radar were used to develop VPR that extended down to about 1.5 km MSL (KRGX profiles terminate at ~2.7 km MSL), to compare with KRGX vertical profiles and also to verify SGM predictions. Figure 4 gives an example of results from a storm during February 2002. VPR from KRGX and the C-band were in close agreement from 7 km down to the base of the KRGX VPR at 2.7 km. Below that level the C-band profiles changed from a positive slope (dBZ increasing downward) to a negative slope (dBZ decreasing downward), presumably due to particle evaporation below cloud base. SGM predictions for dendritic ice particles initiated at about 6.7 km and graupel particles initiated at about 3.4 km produced vertical profiles that resembled the radar VPR quite well. Precipitation rates measured at the surface correlated well with the radar estimates obtained from the base of the profiles, while the use of the KRGX profile alone would have overestimated precipitation by a factor of 1.3 to 2.6. The SGM precipitation rate predictions, determined from the IWC and particle fallspeed, were well below the observed values. This might have been due to the fallspeed or mass-dimensional parameterization in the SGM, but the exact reason has not been determined.

Although Fig. 4 results are promising, the SGM is not ready for implementation in the CSTAR algorithm. The model is quite sensitive to estimated cloud base height and the humidity profile below cloud base. The selection of ice particle habit according to the temperature profile is also a somewhat qualitative decision and variations in habit can also cause large fluctuations in the shape of the profile. Using the SGM in a real time algorithm would require the use of local hydro-meteorological data or short term model (such as the RUC) output. A simpler approach would be to correlate the VPR slope in the lowest kilometer with the relative humidity in the same layer. A comparison of several cases, like those shown in Fig. 4, suggest that the slope is related to humidity in the sub-cloud layer, so that real time measurements through this layer (using surface stations at varying altitudes) might be used to adjust the slope of the downwind VPR's in real time.

Although Objective 3 was not completely accomplished with the SGM being made part of the CSTAR algorithm, the technique was applied and tested using actual VPR, and found to produce reasonable results in a controlled post-analysis situation. The results of the SGM study could lead to the simpler approach noted above, which will be much easier to add to the current algorithm. The added complication of accessing real time meteorological data for use in the radar algorithm is the main reason that the SGM or the simpler method has not as yet been tried.

4. Real time CSTAR algorithm and products used in the Reno NWSFO

Possibly the most important objective of the CSTAR project was to make new products from the precipitation algorithm available to the Reno forecasters. Because no method existed for putting the new algorithm output on the NWS Radar Product Generator, a new method for interpolating the polar radar data to a standard grid was developed and a standard display software package was used to create product images very similar to the 1-hour, 3-hour and storm total images viewed by forecasters. In addition, for real time verification of radar QPE, a tabular output of precipitation gauge accumulations and radar QPE computed at the range gates above the selected gauges was developed. Both the images and tabular output are created each hour and sent by an automated file transfer protocol (FTP) to a computer in the Reno NWSFO. The products can be viewed in real time and compared to the standard NWS products. NWS forecasters also set up a method for putting the products on the Reno NWS Web page: http://www.wrh.noaa.gov/reno/digital/1hour.shtml.

An example of the storm total output product is shown in Fig. 5 for a severe thunderstorm case on 4 August 2003. The storm produced a mudslide as a result of heavy rainfall along the I-80 corridor east of Reno, and also triggered the WSR-88D tornado warning algorithm as the storm intensified in the vicinity of Pyramid Lake. The continuous precipitation swath shown in Fig. 5 is one of the longer ones observed from a convective storm system in the Reno area.

The CSTAR precipitation algorithm has been running in an automated mode since about March 2003. It runs on a Sun Ultra workstation in the Reno NWSFO, the same computer that ingests Level II WSR-88D data via the Base Data Distribution System (BDDS). Some work on all of the main processing programs was performed this past year. The key programs in the data archiving and processing, either modified or created this past year, are as follows:

1) **startcstar** - A program which is activated whenever the Sun is turned on or rebooted. This program then starts the programs **bdds**, **mon_server**, **hour**, and **autostart**. These programs then run either continuously, or activate themselves periodically to check the radar status and determine if new data files exist.

2) **bdds** - This is NWS software that distributes WSR-88D Level II data to outside users. The Sun Ultra is connected to one of the bdds ports and the bdds software allows the Ultra to receive the Level II data.

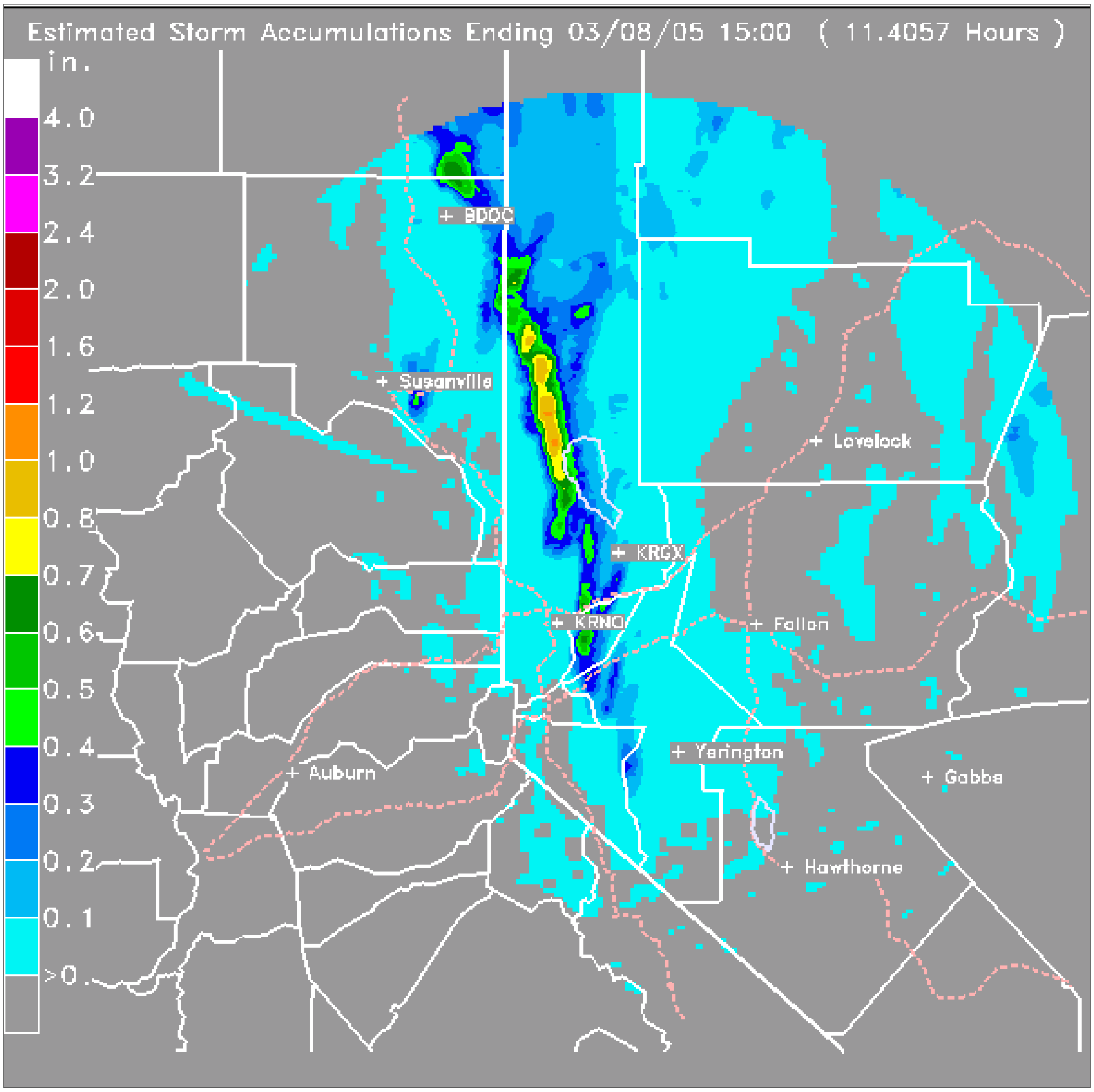

Figure 5. Storm total precipitation plot produced by the CSTAR precipitation algorithm for the period 2000 GMT on 4 August to 0700 GMT on 5 August.

3) **mon_server** - This program looks at the current Level II data and reads the VCP mode, the azimuth, the elevation and the time, and sends the output to the screen, thus providing an easy way to check the radar status.

4) **autostart** - This program frequently checks the VCP mode to decide if data archiving should be initiated. If VCP 11 or 21 is detected, then the data archiving program **ridds2disk** is initiated. The program creates a new data directory (new storm) if the most recent data on the Ultra is a specified number of hours (currently 4) old. If VCP 32 is detected then **autostart** goes back to periodically checking the radar status.

5) **hour** - This is the main control program for radar data processing. It is activated every hour and checks to see if new data exist in the data archive directories of the Ultra. If none exist the program “sleeps” until the next hour. If new Level II files are found then **hour** starts the programs **mapprecip**, **mapit**, and **profprecip**. Currently these programs are run every hour, but the sequence could be changed to run on any time interval.

6) **ridds2disk** - This program controls the archiving of Level II data from the **bdds** program. It was adapted from an NSSL program which used the older RIDDS data distribution system for archiving data to tape. The current version is compatible with the new bdds format and archives data to a hard disk on the Ultra. The file format is the same as the NCDC data archive format for WSR-88D data.

7) **mapprecip** - This program processes the reflectivity data over the entire 360^o azimuth coverage of the radar out to a range specified in the input parameter file. Prior to converting reflectivity factor (dBZ) to a precipitation rate (R) the reflectivity data are adjusted according to the hybrid scan file (specifies the elevation tilt to use at each range bin), the occultation file (adds 0 to 4 dBZ depending on the amount of beam blockage), a clutter file (adjusts dBZ based on long term averages of ground clutter returns), and a VPR file (adjusts dBZ from the height of each range bin down to a constant level using the slope of the VPR). The adjusted dBZ values are then converted to a precipitation accumulation (R times the time interval between scans) through the specified Z-R relationship. An output file of 1-hour accumulation values in radar polar coordinates is created. The 3-hour and storm total files are created by adding the current hour to results from the previous hours.

8) **mapit** - Mapit takes 1-hour, 3-hour and storm total output files in radar coordinates and interpolates the values to a uniform grid with spacing (currently 2 km) specified by the input file. The 2-km grid data are then color contoured onto a map of the KRGX coverage area and saved as NCARGRAPHICS metafiles. For display in the Reno NWSFO the metafiles are converted to more standard image files and saved in a special directory of the Ultra.

9) **profprecip** - This software is similar to **mapprecip** but computes precipitation accumulation only for range bins corresponding to the locations of a specified set of precipitation gauges. The output is a set of three tables of radar precipitation values for each gauge location for the previous 1-hour, 3-hour and storm duration. The output file is then used by the program **querydb** to match gauge accumulations to the radar QPE.

10) **querydb** - Each hour this program is initiated and reads a hydromet data file that is sent to the Ultra from the Reno NWS hydromet computer. The file contains a vast amount of hydrological and meteorological data from observing sites throughout the Reno NWSFO forecast zones. **Querydb** searches the file and strips off just the precipitation data from the set of gauges being used for the radar comparison. These data are then appended to a precipitation data base file that is compiled for an entire water year (1 Oct to 30 Sept). Using start and end times specified in the output file of **profprecip**, the program then computes 1-hour, 3-hour and storm total accumulations for the gauges having radar precipitation estimates. The radar output file is rewritten to produce the final two-column output containing both radar and gauge values in each table. The output file is then automatically transferred to an NWS computer for display in the forecast office.

5. Staff support and publications

The following DRI staff received support from the CSTAR project during the past year. Mr. Arlen Huggins, the P.I., supervised the work, guided the development of the various algorithm components, performed a considerable amount of the radar and precipitation data analysis, prepared presentations, communicated with Reno NWSFO staff, and wrote the bulk of the reports. Dr. David Kingsmill collected all of the DRI C-band data during the winter of 2001-02 and supervised the data reduction and data comparison with the WSR-88D. He also contributed to reports and presentations. Dr. David Mitchell worked with the SGM, making numerous modifications to enable it to be initiated from radar VPR data. Dr. Mitchell also contributed to presentations and reports. Mr. Sam Keck wrote all new processing and display programs required for the radar algorithm and constructed all the complicated script files needed to run each of the programs in real time in the Reno NWSFO. Dr. Morien Roberts created and frequently modified the precipitation data base and analysis program, and combined the radar and precipitation data into its final output format. Mr. Kevin Keating, an undergraduate student, archived the Level II data at DRI and did the bulk of the post-processing runs with the various VPR and precipitation algorithm programs. Finally, Dr. Huaqing Cai, a post doctoral appointment at DRI for part of 2002, did the final processing of the DRI C-band and WSR-88D data onto equivalent three-dimensional grids in order to create vertical profiles from the same volume in space.

The project produced no reviewed papers in this reporting period. Many of the results reported here were presented at the 9th Annual Workshop on Inter-mountain Weather Prediction in Salt Lake City in November of 2002 (Huggins et al., 2002). The complete presentation can be viewed on the internet at: http://www.ciasta.dri.edu/presentations.html. Several other presentations that were made during the three years of the project can be found at the same address.

6. References

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Huggins, A.W. and D.E. Kingsmill, 1999: Quantitative precipitation estimates from a mountain-top WSR-88D: Data pre-processing considerations. Preprints of 29th International Conference on Radar Meteorology, AMS, Montreal, Quebec, Canada, 709-712.

Huggins, A.W., D.E. Kingsmill, D. Mitchell, and Q. Cai, 2002: Vertical profiles of reflectivity: Use in a WSR-88D precipitation algorithm and their extension below WSR-88D sampling levels. Presentation at 9th Annual Intermountain Weather Prediction Workshop, Salt Lake City, Utah, November, 2002.

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Seo, J.D., J. Breidenbach, R. Fulton, and D. Miller, 2000: Real-time adjustment of range-dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity. *J. Hydrometeor.*, **1**, 222-240.

TASK III: CLIMATE RESEARCH AND SERVICES

Development of National Indexes for Monitoring Climate Variability Relations to Air Quality

Project Personnel: Kelly Redmond (DRI/WRCC); Kenneth Kunkel (Univ. of Illinois/MRCC); Art DeGaetano (Cornell Univ./NRCC); support staff at RCCs
Task: Climate Research and Services
Goal: Develop quantitative indicators of climatological and meteorological factors pertinent to air quality and investigate relations of such indicators to larger scale patterns of climate variability

This work has three components.

Western Regional Climate Center. A widespread search was conducted for a post-doc to develop the WRCC portion of the project. When a suitable candidate could not be found, Dorothea Ivanova of DRI agreed to work half-time on the project prior to concluding her dissertation. The WRCC role in the project is to develop indices based on the historical and current radiosonde profiles. The first such index is to consist of monthly counts of inversions with specified properties across the country, expressed in the form of anomaly maps. WRCC has a portion of the period-of-record radiosonde data set in its holdings, but needed to supplement that with the remainder of the national set. This request turned out to be rather complex, so for interim work, the FSL (Forecast Systems Lab) version of the data set was obtained. This will be used until the full archive set can be obtained from NCDC. These have been converted into an internal binary code. Another set of programs is being built to ingest, decode and convert to the same format the soundings obtained from operational feeds. The program to produce the counts has already been written. The next step will then be to portray these counts on a web accessible map of North America. During this process, unexpected differences were encountered between the NCDC archive and the FSL data set. Also noted were unusual statistical properties of some of the time series. These will be investigated further.

Midwest Regional Climate Center. This work involves both Ho-Chun Huang and Ken Kunkel of MRCC. One major aspect of their work is to determine whether model based information can supplement or replace information based entirely on in situ measurements. A set of stations and associated grid points was selected and compared, by using mixing depths. The time series from the two sources correlated at about the 0.7 to 0.8 level in general, for the summer months of most interest. This level of correlation appears to be at least marginally useful. They further used multiple regression to determine which climatic elements or combinations thereof had the best correlation to measures such as ozone concentration and other measures. Their work is summarized in Huang and Kunkel (2003). The elements with strongest correlations were daytime temperature, incident solar radiation, fractional cloud cover, cloud optical depth, and daytime maximum temperature.

Northeast Regional Climate Center. Art DeGaetano and (later, and primarily) Dan Graybeal spearheaded this work, dealing with in situ measurements in the Northeast and New England, and their potential relation to climate and meteorology elements. Their work so far has concentrated on ozone measurements in the Northeast, which is correlated with regional temperature, large scale stagnation, and solar energy. They generally found correlations of 0.5 to 0.8. Additional work showed that the eastern United States shows a more coherent signal than the western United States, using the methods chosen.

Research of the NOAA Regional Climate Centers 2002-2003

Project Personnel: Richard Reinhardt (DRI/WRCC); Kenneth Hubbard (Univ. of Nebraska, Lincoln/HPRCC); Steven Hilberg (Univ. of Illinois/MRCC); Arthur DeGaetano (Cornell Univ./NRCC); Michael Janis (So. Carolina Dept. of Natural Resources/SERCC); Kevin Robbins (Louisiana State Univ./SRCC); support staff at all RCCs
Task: Climate Research and Services
Goal: Provide climatic data and information services to all fifty states and U.S. territories

Introduction

NOAA's Regional Climate Centers (RCC) Program provides climatic data and information services to all fifty states and U.S. territories. The Program is administered by the National Climatic Data Center (NCDC) and is funded through CIASTA. The RCCs are located at: Cornell University, Ithaca, NY; Dept. of Natural Resources, Columbia, SC; Louisiana State University, Baton Rouge, LA; Illinois State Water Survey, Champaign, IL; University of Nebraska, Lincoln, NE; and, the Desert Research Institute, Reno, NV.

The mission of each RCC is to deliver a regionally relevant suite of contemporary climate products and services to all sectors of the U. S. economy comprising individuals, businesses, governmental agencies, and academe. These services include the provision of high quality climatic data and information as well as assistance on their application and interpretation. Since the Department of Commerce General counsel determined that only research activities could be awarded through cooperative agreements, they were the only activities performed by the RCCs through CIASTA this past year. The research performed at the RCCs is primarily applied to data improvement and accessibility, and creating new information in anticipation of emerging national and regional economic needs.

Although the details of the research performed at each of the RCCs may vary due to differences in regional applications, four major research thrusts were common to each Regional Center.

Network Performance

Climatic data are acquired from a variety of networks. The oldest, and therefore most important climatically, is the Coop Network. As the sophistication of climatic data users increases, their demand for increasingly timely data increases too. Because the first application of much of the Coop data is for short-range weather prediction, the data available in near real time is often corrupted. There are a number of reasons for this. The goal is to identify all of them and fix the ones we can, and alert the National Weather Service to the rest. Due to these factors, the quality control processes in place at the National Climatic Data Center (NCDC) require months to ensure a reasonably high quality result.

Quality Control Procedure Development

As mentioned above, NCDC has a number of quality control processes in place. The RCCs are developing new procedures to handle near real time data, and to meet the unique needs of each region. For example, an algorithm that relies on nearest neighbor values is likely to produce erroneous estimates for replacement of missing values in the West due to the high gradients of both temperature and precipitation with elevation. While the RCCs are working toward improved QC algorithms for their own regions, there is a common goal of improved understanding of climate variability throughout the country. The RCCs are also developing QC procedures for some of the old data sets that have yet to be digitized, and for data acquired from non-NOAA sources.

Real Time Monitoring

The RCCs acquire near real time data from a variety of sources at local, state, regional, and federal levels. These data are used to monitor and assess regional climatic conditions and impacts. For example, they are used to produce detailed "percent of average" products, which help the states in their regions quantify the extent of drought they may be experiencing. Monitoring is also more than data acquisition. Monitoring must relate current climatic conditions to the activities that are occurring. For example, in agriculture there are times in a crop's development when it dryness does not impact the final result at all. To meet the needs of such situations the RCCs are developing the capability to compute "normals" dynamically, i.e., for any given period of time over any given number of years.

Climate Variability and Trends

The work is intended to characterize, understand, and predict important aspects of climate, which are required to meet the demand for finer spatial and temporal resolution. Better knowledge of the spatial structure of temporal characteristics of climate variations is needed, especially at smaller scales. For example, the West is experiencing significant warming in winter and spring months. The spatial and elevational distribution of the trends has important implications for snow pack quantity, and when it becomes available for use. Such impacts on water supply can have huge impacts in many other economic sectors.

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TASK IV: AIR QUALITY RESEARCH

Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study

Project Personnel: Mark Green; Vic Etyemezian; Djorde Nicolic (DRI/DAS)
Task: Air Quality Research
Goal: Understand the long-range, transboundary transport of visibility-reducing particles from regional sources in the U.S. and Mexico and to quantify the contributions of specific U.S. and Mexican sources (or source reigions) responsible for poor visibility at Big Bend NP.

BRAVO includes an extensive field study (July-October 1999) with tracer release and monitoring, aerosol and optical monitoring, upper-air meteorological measurements and source characterization measurements. DRI is responsible for many components of the study, including technical management assistance, creation and maintenance of the BRAVO database, data analysis, a portion of the optical monitoring, emissions inventory and source characterization.

The BRAVO study is close to completion, with a draft final report expected by the end of September 2003.

Objectives for the period July 1, 2002: June 30, 2003:

1) Prepare sections for the BRAVO draft final report
2) Participate in the evaluation and reconciliation of results
3) Present study results at conferences and in the refereed literature

Accomplishments for the period July 1, 2002: June 30, 2003

1) Sections of the draft final report were prepared for the following topics:
   a) Transport climatology representativeness for the July-October 1999 study period compared to the 5-year (1998-2002) July-October average.
   b) Evaluation of MM5, EDAS, and FNL wind fields by comparison to radar wind profiler data
   c) Source attribution of particulate sulfur and sulfur dioxide at the BRAVO 6 hour sampling sites in and near Big Bend National Park to local and regional sources using the TAGIT approach (also published in the Journal of the Air and Waste Management Association.

   These report sections are presented below.

2) Reconciliation and evaluation of results- two meetings were attended and several conference calls where results from the various source attribution methods were compared and evaluated . This included comparison of results for individual episodes a well as the entire study period. A paper was presented at the annual AWMA conference in June 2003 that presented results from the various methods. The reconciliation process is near completion.

3) The following peer-reviewed article was published:

Green, M., Kuhns, H., Pitchford, M., Dietz, R., Ashbaugh, L., and Watson, T., 2003. Application of the Tracer-Aerosol Gradient Interpretive Technique (TAGIT) to sulfur attribution for the Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study. *J. of Air & Waste Mgmt. Asso.,* **53,** 586:595.

The following conference proceedings were published and presented:

Green, M., Gebhart, K., Schichtel, B., and Barna, M. (2003) An Overview of Methods Used for Particulate Sulfur Source Attribution for the Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study and Some Preliminary (Unreconciled) Results. Paper #69833 Presented at the 96th annual conference of the Air & Waste Management Association, San Diego, CA, June 23-26, 2003.

Schichtel, B., Green, M., Barna, M., Seigneur, C., Pun, B. (2002). Evaluation of Atmospheric Transport and Dispersion Models using Perfuorocarbon Tracer Data for the BRAVO Study. Presented at AGU annual meeting, San Francisco, CA, December 2002.

Transport Climatology Representativeness for BRAVO Study Period

When considering results from the BRAVO Study, it is of interest to consider the representativeness of the BRAVO study period of July through October 1999. Here the frequency of transport from different areas to Big Bend National Park for July through October for each of the years 1998 through 2002 are compared.

Methodology

The HYSPLIT backtrajectory model was used with default conditions (e.g. model vertical velocity) and the FNL meteorological archive (ftp://www.arl.noaa.gov/pub/archives/fnl). The FNL meteorological fields were used because they have a more complete data set for the period than the EDAS fields, although the grid spacing of 190.5 km is coarse compared to the EDAS spacing of 80 km. The FNL archive is described in detail at http://www.arl.noaa.gov/ready-bin/fnl.pl.

Backtrajectories were started at one-hour intervals for the 4-month period and were run for 192 hours (8 days). The 8-day period was selected to allow for possible transport from the eastern United States during relatively light wind conditions to be identified. Three starting heights were used: 10 m, 500 m, and 1500 m above ground level. Typical afternoon mixing heights in south Texas (Del Rio soundings) during summer are about 2500 m, so these heights represent lower to middle-upper daytime mixed layer locations.

Residence time was calculated by counting the number of backtrajectory endpoints (hourly locations) in each one-degree latitude by one-degree longitude area and dividing by the total number of endpoints. The gridded residence times were then contoured. Maps of residence time were generated for each year (1998 through 2002) at each level (10, 500, 1500 m AGL). Difference maps of residence time for each year minus the 5- year average residence time at each height were also computed to illustrate differences of each year from the 5-year mean.

Results

Figure 1 compares the residence times for July-October 1999 to the 1998-2002 July-October 5-year average residence time for the 10, 500, and 1500 meters AGL starting heights. Figure 2 shows the difference between July-October 1999 and the July-October 5-year average at each height. Figure 1 shows that as starting elevation of the backtrajectories increases, transport distance are longer (higher wind speeds with height), and there is more variability in wind direction. The general flow patterns for 1999 and the 5-year average are similar, but some differences can be noted. At all 3 heights during 1999 there was less transport from the eastern U.S. as compared to the 5-year average for July-October. At 10 meters, 1999 has less flow over all of Texas except the Panhandle and far southern Texas than the 5-year average, with more flow over the border area and far northeastern Mexico. At 1500 meters, 1999 had more frequent flow over southeastern Texas, northern Mexico, and Louisiana.

Figure 1. Residence times for July-October 1999 and the 5-year July-October average, for 10, 500, and 1500 meter starting heights.

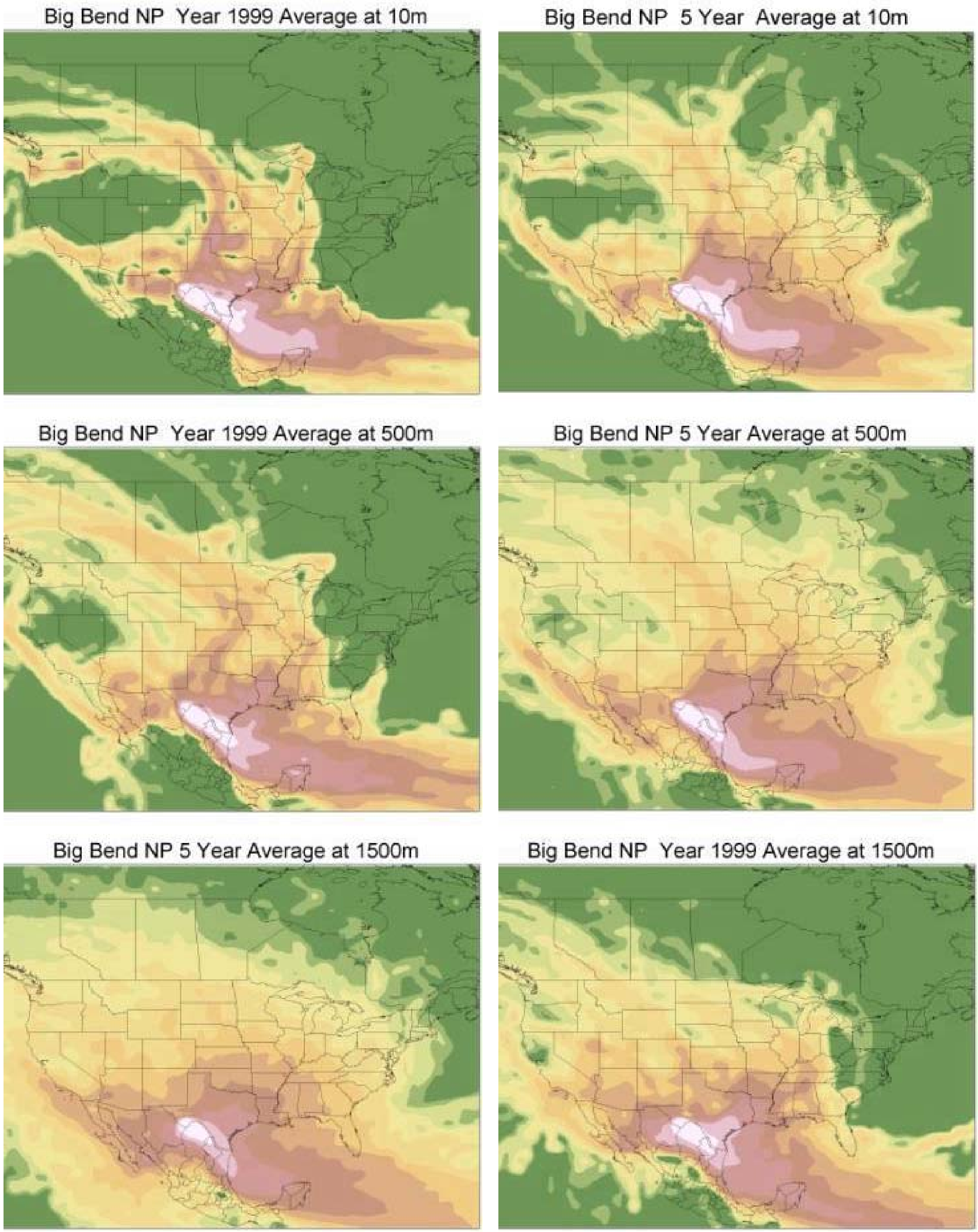


Figure 2. Differences in residence time between July-October 1999 and the 5-year (1998-2002) July-October average. Legends for Figures 1 and 2 are also shown.

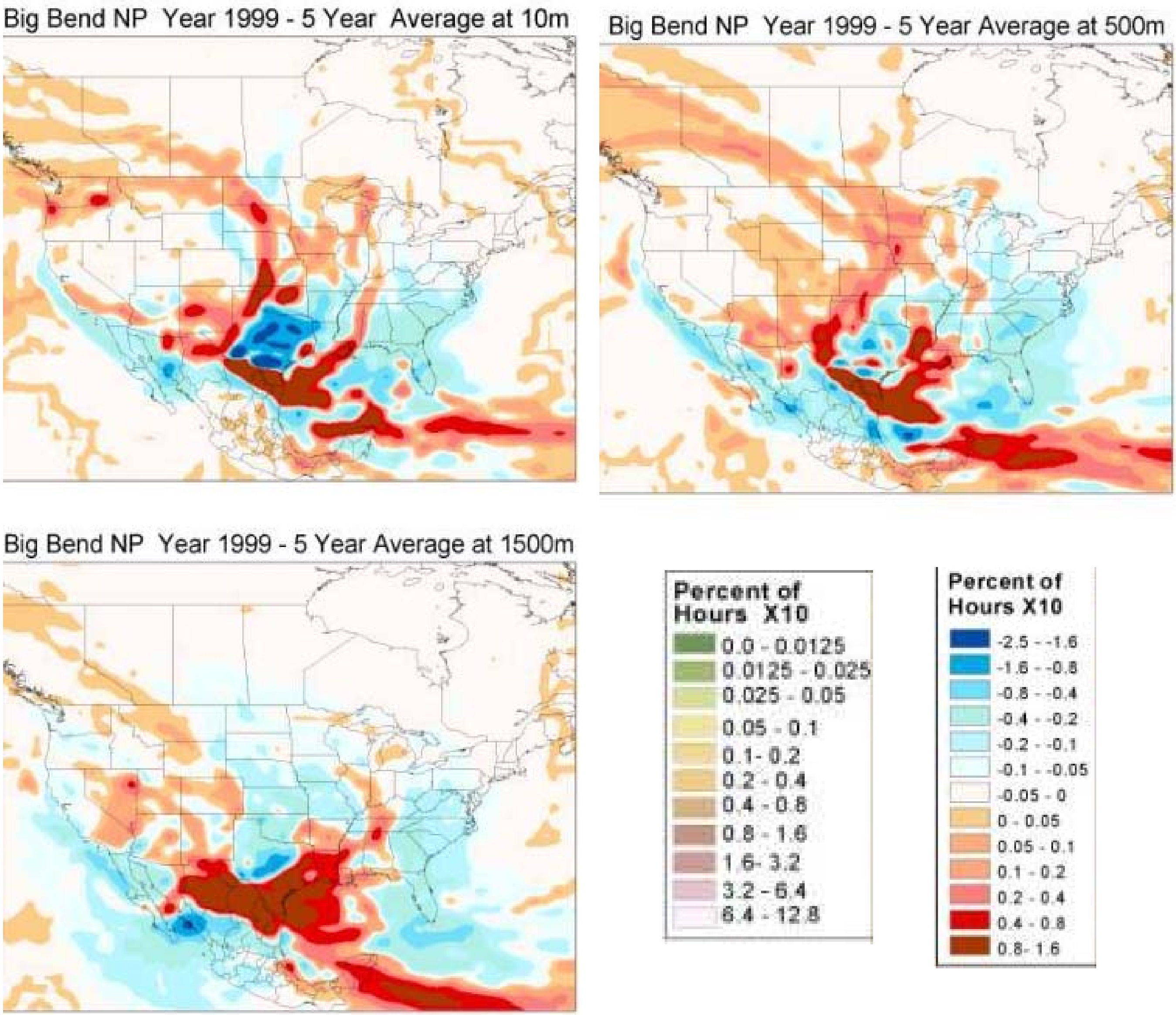
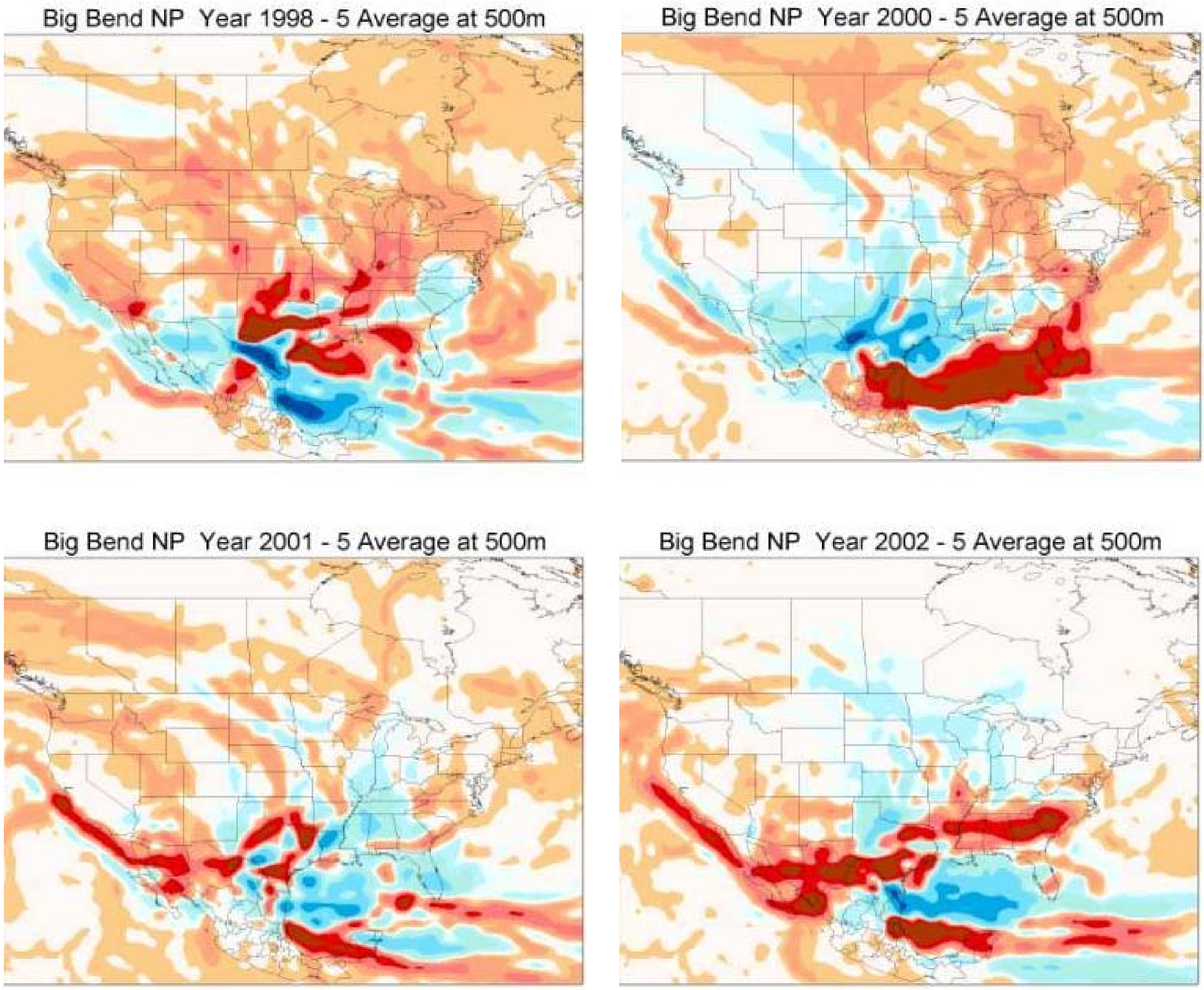


Figure 3 shows the difference from the 5-year mean for 1998, 2000, 2001, and 2002. In 1998, there was more frequent flow from the Ohio River Valley, 2001 had less frequent flow from the eastern US, and 2002 had a higher frequency of flow from the southeastern US than the 5-year average.



Conclusion

Variations in year-to-year July-October transport frequency were noted for the 5-year period. In 1999, there was less than usual frequency of flow from the eastern US and central Mexico. Flow along the Texas/Mexico border area and far northeastern Mexico was more frequent than on average. Flow from eastern Texas was less frequent in 1999 for the 10 meter backtrajectories, but more frequent than average for 1500 meters start heights. All years showed areas of notable departures from the 5-year mean. The July-October 1999 BRAVO study period appears to be within the typical variation in transport frequencies, i.e. it is not atypical.

Comparison of MM5, EDAS, and FNL winds to radar wind profiler winds

Introduction

MM5, EDAS, and FNL wind fields were used for several source and receptor models applied for the study. REMSAD and CMAQ used MM5 fields. The receptor models used either MM5 or a combination of EDAS (July-September) and FNL (October). For some receptor models, both MM5 and the EDAS/FNL combination were used, with somewhat differing attribution results. It is of interest to evaluate the accuracy of the wind fields used to help reconcile the results.

Methodology

Wind data from the radar wind profilers were compared to wind data for the MM5, EDAS, and FNL output four times per day, at 6am, noon, 6pm, and midnight Central Standard Time. The radar wind profiler data is available for 60 meter thick layers up until about 2000-2500 m AGL, then every 100 m up to about 3500-4000 m AGL. The models have varying layer thicknesses, typically closer near the ground, and then telescoping upward. A simple approach was used to obtain "paired" data for the models and radar wind profilers. We selected the single radar wind profile level closest to the model layer height for comparison.

Several measures were used to compare model and RWP winds, including:

- Average model wind and average RWP wind speed
- Magnitude of vector difference between modeled and RWP winds.
- Average difference in wind direction (degrees)
- Average absolute value of wind direction difference
- Percent of periods where model and RWP wind directions were within 20 degrees and 30 degrees
- Percent of wind directions from 8 general directions (N, NE, E, SE, S, SW, W, NW) of model and RWP by layers- 0-500 m, 500-1500 m, >1500

The typical number of model/observation comparisons by layer for each observation time are shown below:

Level/Model	MM5	EDAS	FNL
0-500 m	4	2-3	1
500-1500 m	5	4	1
1500-3800 m	5	4	1

The FNL fields have few vertical levels within the lower troposphere.

Because the EDAS fields were not available for October 1999, the summary of MM5 fields was done for the July- September and October periods separately. This facilitates the comparison of the EDAS and MM5 performance measures for the same temporal periods. The performance of the MM5 fields can be compared to that of the FNL fields for the month of October.

Results

Some summary statistics for the MM5, EDAS, and FNL comparison to the radar wind profilers for the period July-September 1999 are shown in Table 1.

Table 1. Comparison of MM5, EDAS, and FNL winds to radar wind profiler winds for July-September. Data is averaged over all vertical levels and over all observation times. The column variables are described under the first 5 items in the bulleted list shown earlier.

MM5, EDAS, and FNL evaluation for July-September

Location	Model	ModelWS	rwp ws	Diff WS	M- rwp wd	abs value	20 deg?	30 deg?
Big Bend	MM5	5.53	5.57	4.18	-3.19	38.54	0.37	0.52
Big Bend	EDAS	5.32	5.70	4.44	-6.97	43.20	0.33	0.47
Big Bend	FNL	6.05	5.69	5.66	-6.33	52.12	0.25	0.37
Llano	MM5	6.16	5.87	3.77	-6.17	31.19	0.52	0.67
Llano	EDAS	5.86	5.96	3.40	-3.19	31.04	0.53	0.67
Llano	FNL	5.55	6.22	6.53	-4.38	43.99	0.34	0.49
Brownsville	MM5	7.16	7.04	2.92	-3.62	20.24	0.67	0.81
Brownsville	EDAS	6.84	7.11	2.77	-2.80	20.58	0.67	0.79
Brownsville	FNL	6.73	7.19	4.53	-4.58	32.20	0.45	0.60
Eagle Pass	MM5	6.75	7.63	4.00	-3.37	26.29	0.56	0.71
Eagle Pass	EDAS	6.87	7.83	3.80	0.93	24.04	0.60	0.76
Eagle Pass	FNL	6.47	7.97	5.28	4.09	34.08	0.44	0.61

For both MM5 and EDAS, the model average wind speeds were quite close to the RWP average wind speed, although there was a slight underprediction of wind speed by both models at Eagle Pass. The FNL showed somewhat larger differences compared to the RWP. The average vector differences in model and RWP wind speeds were the least at Brownsville for all 3 models. A slight counterclockwise bias of a few degrees in wind direction was noted at all sites for both models (except EDAS and FNL at Eagle Pass). The average absolute value of wind direction differences ranged from about 20 degrees for EDAS and MM5 at Brownsville to about 40 degrees for the models at Big Bend. For the FNL, differences were larger, averaging about 30 degrees at Brownville and 50 degrees at Big Bend. It will be shown that much of the difference at Big Bend is at the lower levels, likely due to channeling of flow by local terrain features. The fraction of model wind directions within ± 20 degrees ranged from one-quarter at Big Bend for FNL to two-thirds at Brownsville for EDAS and MM5. The fraction of model winds within ± 30 degrees ranged from about three-eighths for FNL at Big Bend to about four-fifths at Brownsville for EDAS and MM5.

The FNL performed worse than EDAS and MM5 for all criteria except average wind direction difference (bias), where it was about the same. Some of this difference may be due to the use of

a single radar wind profiler level to compare with the comparatively very coarse FNL vertical layers. Perhaps averaging the RWP data within each FNL layer would give better results.
Comparing Tables 1 and 2, it can be seen that MM5 performance for October was much worse than for the July to September period, while the FNL performance was slightly poorer for October than for July-September. The magnitude of the MM5 vector wind speed errors increased from 50-100% during October compared to July-September. Bias in wind directions increased substantially to (16-23 degrees counter-clockwise). The average absolute value of the wind direction difference increased substantially and the fraction of winds within ± 20 degrees and ± 30 degrees decreased substantially.

Even though the FNL performance degraded during October, the FNL performed about as well as MM5 for October. Wind speed differences were somewhat higher for FNL than MM5, but wind direction bias was less for FNL compared to MM5. Fraction of wind directions within 20 and 30 degrees was very similar for the models, with a slight edge to MM5.

Table 2. MM5 and FNL performance for July-September compared to October.

MM5 and FNL evaluation for October

		ModelWS	rwp WS	Diff WS	M- rwp wd	abs value	20 deg?	30 deg?
Big Bend	MM5	5.20	6.15	6.18	-21.30	58.92	0.22	0.31
Big Bend	FNL	6.12	6.67	7.05	-12.00	64.31	0.22	0.32
Llano	MM5	6.07	7.00	6.14	-16.31	49.60	0.33	0.45
Llano	FNL	6.46	7.73	6.22	2.22	50.40	0.36	0.46
Brownsville	MM5	6.77	6.47	5.76	-16.51	44.58	0.35	0.47
Brownsville	FNL	6.59	6.68	6.16	6.99	50.53	0.31	0.43
Eagle Pass	MM5	6.12	7.60	6.45	-22.86	46.34	0.34	0.46
Eagle Pass	FNL	6.86	8.28	7.01	4.55	52.01	0.33	0.42

Comparison of model and RWP wind roses

In this section we compare the percent of wind directions from 8 general directions (N, NE, E, SE, S, SW, W, NW) of model and RWP by layers- 0-500 m, 500-1500 m, and >1500 m. The comparisons are done for the period July-September 1999 because we have MM5 and EDAS winds for these periods (no EDAS for October).

Llano

The comparison of frequency of MM5 and EDAS winds to radar wind profiler winds at Llano are compared in Figure 1. In the lowest 500 m, the wind direction frequency compared well to the radar wind profiler for both models. For the layer 500 m to 1500 m, the EDAS frequency was quite similar to the RWP frequency, while the MM5 showed more E and SE winds and fewer S and SW winds than did the RWP. For the 1500- 4000 m layer, both models showed substantial differences from the RWP, in particular with more easterly winds and fewer northerly winds.

Big Bend National Park

The comparison of frequency of MM5 and EDAS winds to radar wind profiler winds at Big Bend National Park are compared in Figure 2. The RWP winds at the lowest level are mainly from the south, while the models show winds predominantly from the SE and E. The low level winds at Big Bend are most likely due to channeling by local terrain; the model winds would not be expected to resolve this channeling. At the 500 m – 1500 m level, there is better agreement between the models and the RWP as the RWP winds shift more toward the southeast and east. The best agreement is for the layer above 1500 m, although both models are a bit low on northerly winds (especially MM5) and high for easterly and southeasterly winds.

Eagle Pass

Figure 3 compares Eagle Pass MM5 and EDAS winds to RWP winds for July-September. The models and RWP show that southeasterly winds dominate, particularly at the lowest level where 60% of observations show southeasterly winds. EDAS somewhat overpredicts the frequency of SE wind at 0-500 m, while MM5 has somewhat greater frequency of easterly winds at the expense of southerly winds observed. At 500-1500 m, the frequency distributions of both models match well with observations.

Brownsville

Brownville model and observed wind are shown in Figure 4. The MM5 distribution very closely matches the observed distribution at the 0-500 and 500-1500 m levels. EDAS matches observations well over the 500-1500 m layer, but underestimates SE and NE winds and overestimates southerly winds.in the 0-500 m layer. Both models show some discrepancy from observations above 1500 m.

Vertically averaged MM5 and EDAS comparisons

Figure 5 shows the average MM5, EDAS, and RWP wind direction frequency distributions averaged over all vertical levels at Llano, Big Bend, Eagle Pass and Brownsville.

October comparisons for MM5

Because the October statistics showed poorer performance for MM5 compared to the July-September period, it is worth looking at October in some detail. Figure 6 compares MM5 wind direction frequency distribution to RWP distribution for October. Averaged over all levels, the MM5 frequency distribution is close to the observations. For each layer, particularly the 0-500 m layer, differences are more pronounced. Comparison of the 0-500 m level performance for July – September (Figure 4) to that for October illustrate why the performance statistics were so much worse for October at Brownsville.

Figure 7 compares MM5 to RWP wind direction frequencies for the 500 - 1500 m levels at Eagle Pass for July to September and October. Much better agreement can be noted for the July-September period than for the October period.

Summary

MM5 and EDAS performance was similar for the July to September period for which both models were available. MM5 performed similar to or slightly better than FNL for October, with the exception of a pronounced counter-clockwise bias for MM5 winds in October. The MM5 performance was much worse for October than for the July-September period.

A clear preference for the MM5 or EDAS/FNL combination of wind fields has not been established by this analysis.

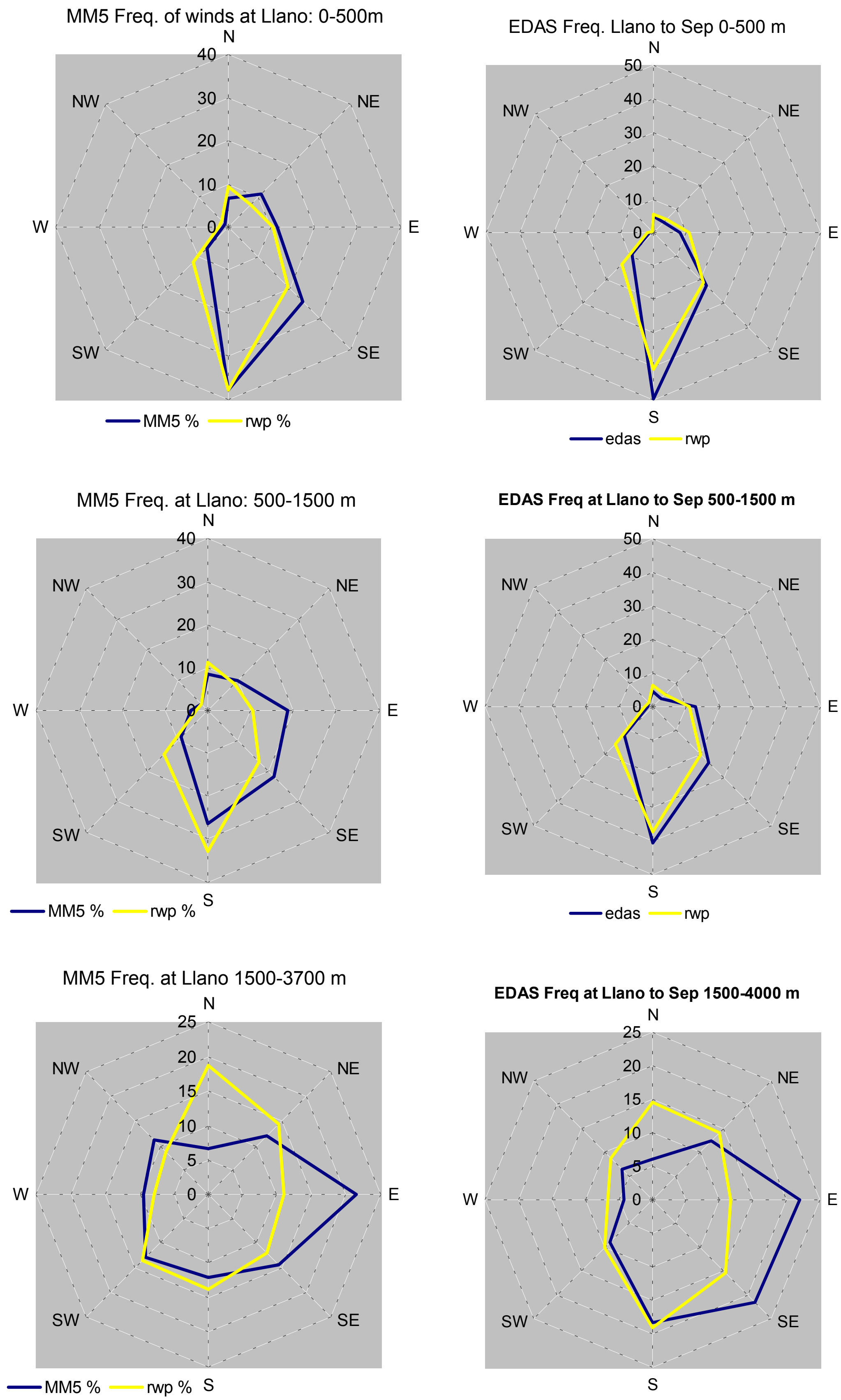


Figure 1. Comparison of MM5 and EDAS wind direction frequency to radar wind profiler winds by level at Llano.

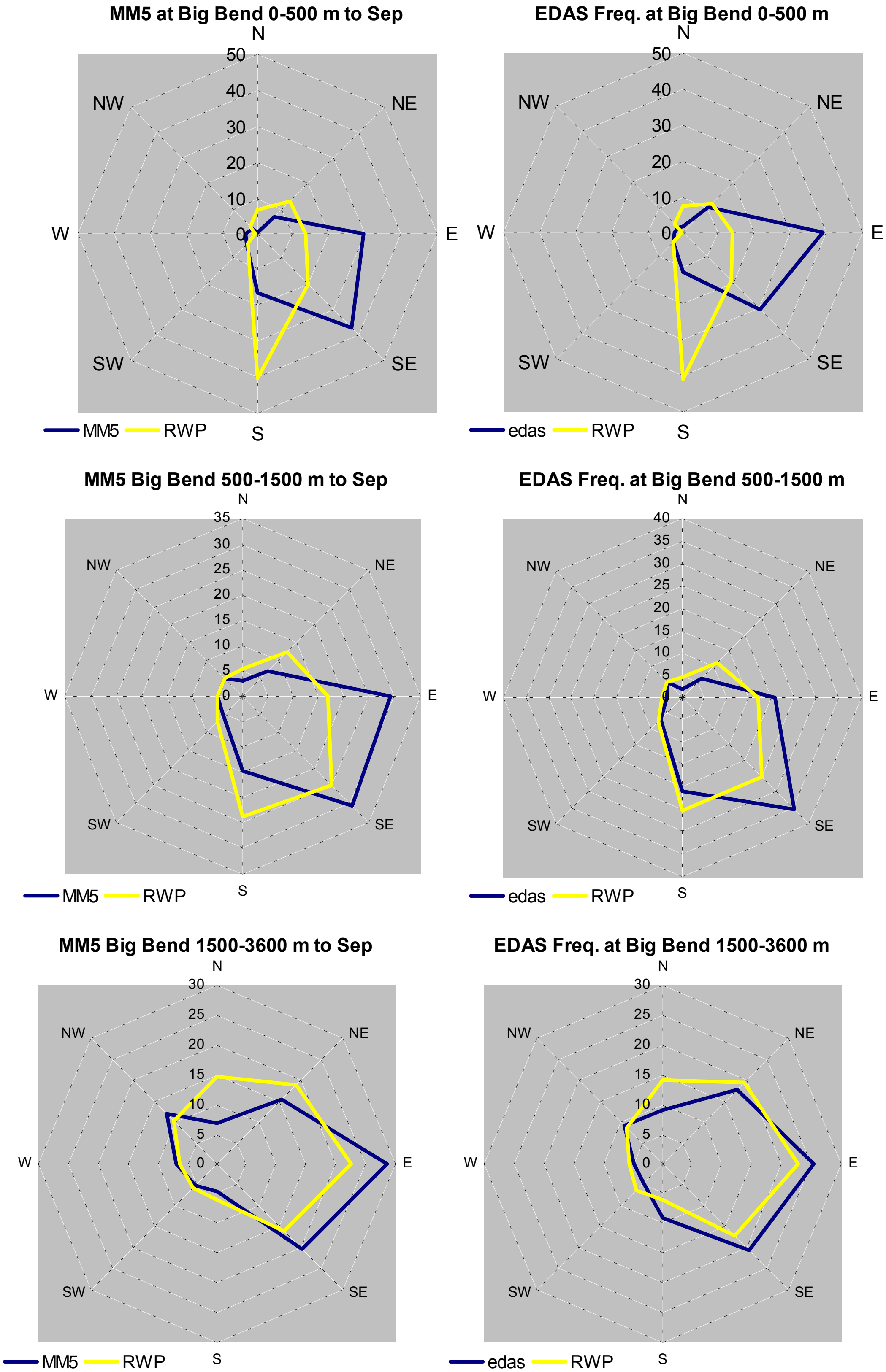


Figure 2. Comparison of MM5 and EDAS wind direction frequency to radar wind profiler winds by level at Big Bend.

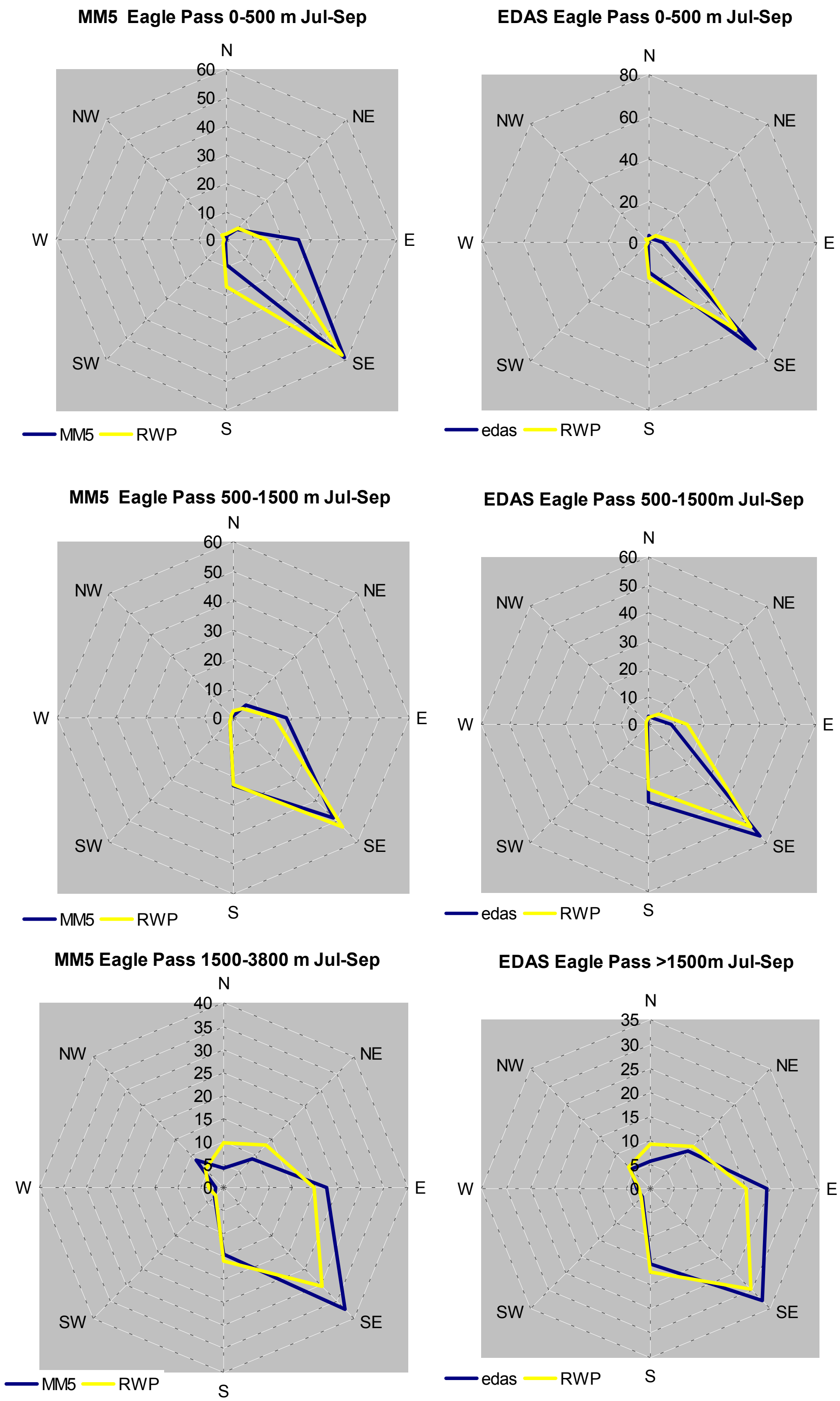


Figure 3. Comparison of MM5 and EDAS wind direction frequency to radar wind profiler winds by level at Eagle Pass.

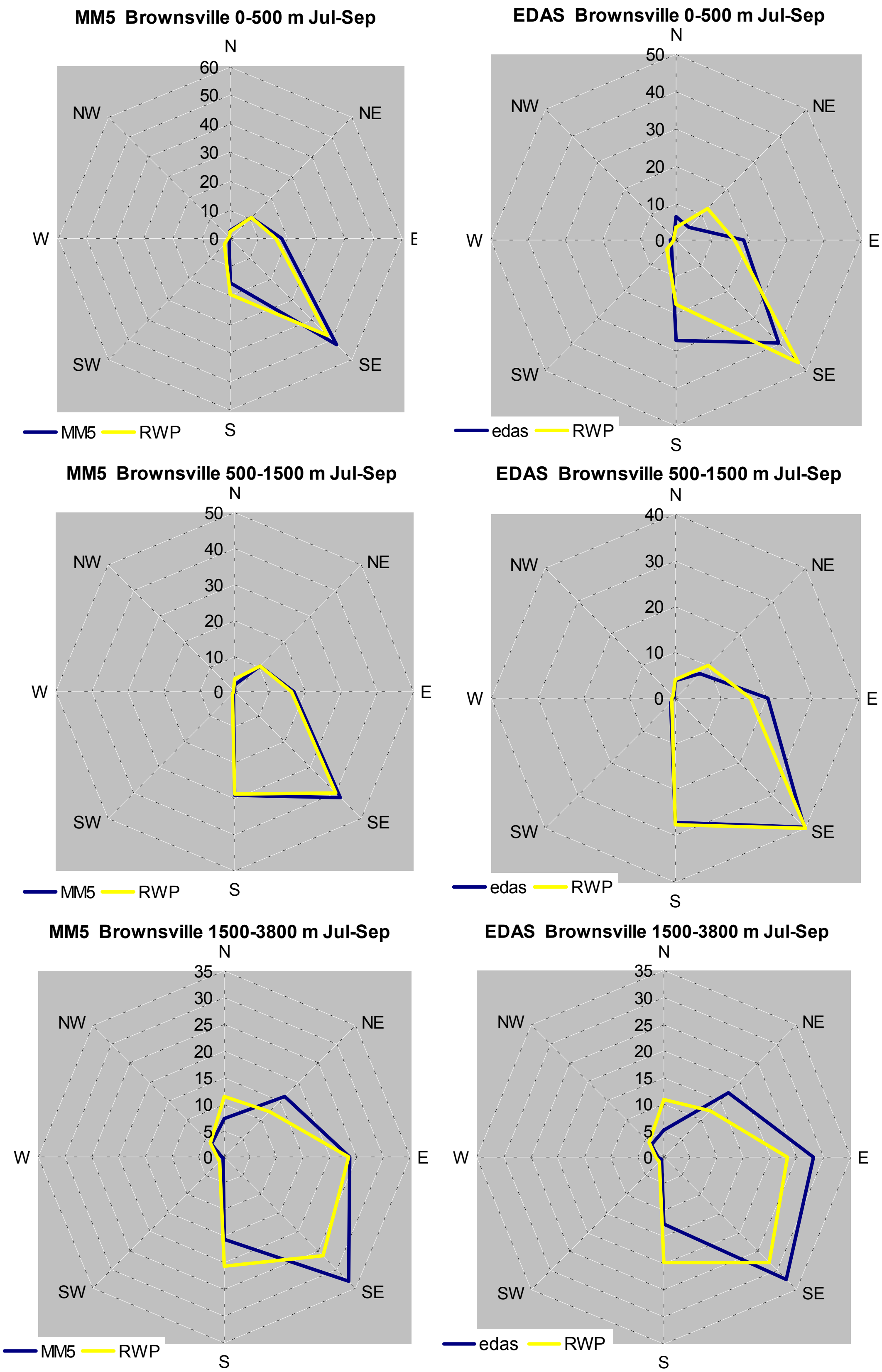


Figure 4. Comparison of MM5 and EDAS wind direction frequency to radar wind profiler winds by level at Brownsville

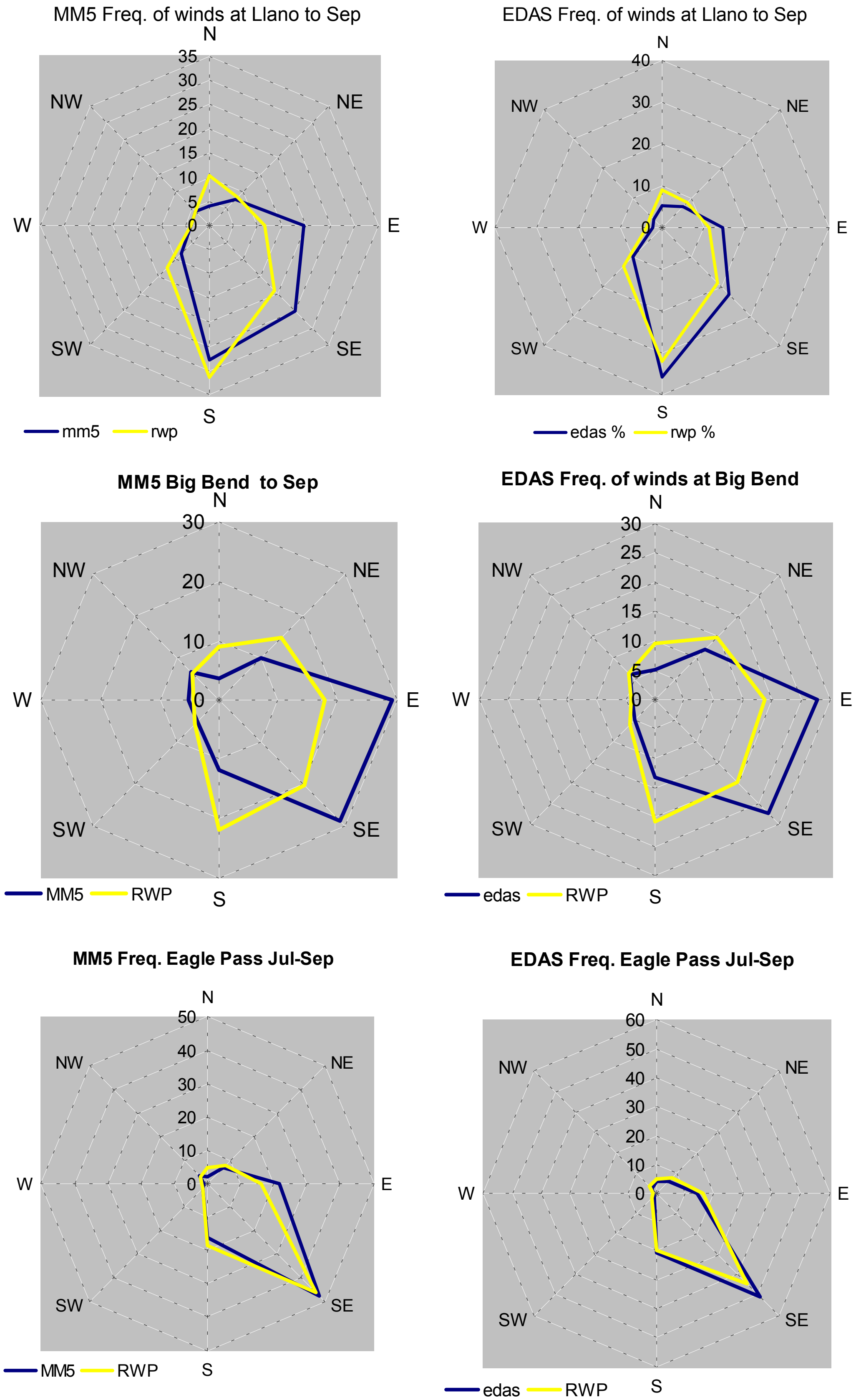


Figure 5. MM5 and EDAS comparisons to RWP, averaged over all vertical levels at Llano, Big Bend and Eagle Pass,

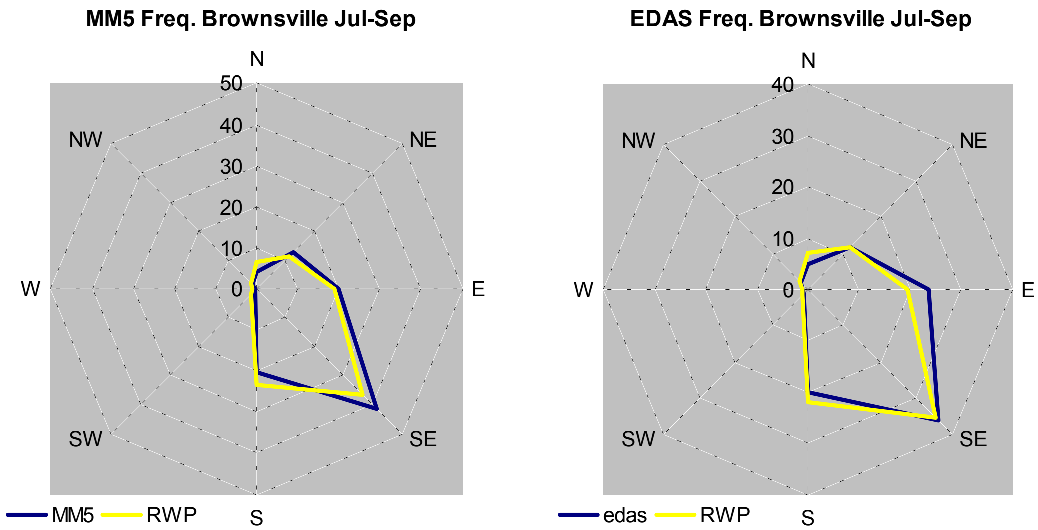


Figure 5 (continued) MM5 and EDAS comparisons to RWP, averaged over all vertical levels at Brownsville.

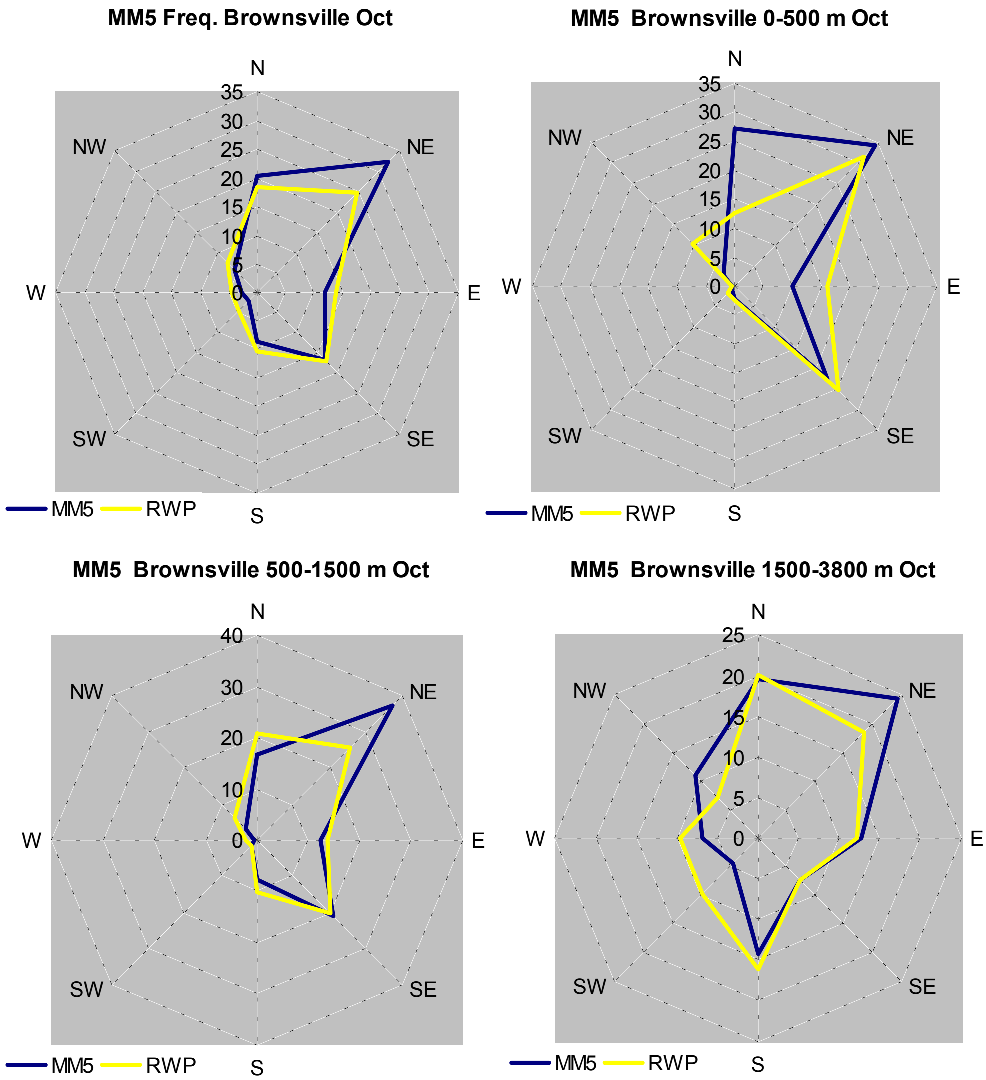


Figure 6. Comparison of MM5 to RWP at Brownsville, October 1999. Firt panel is average over all levels

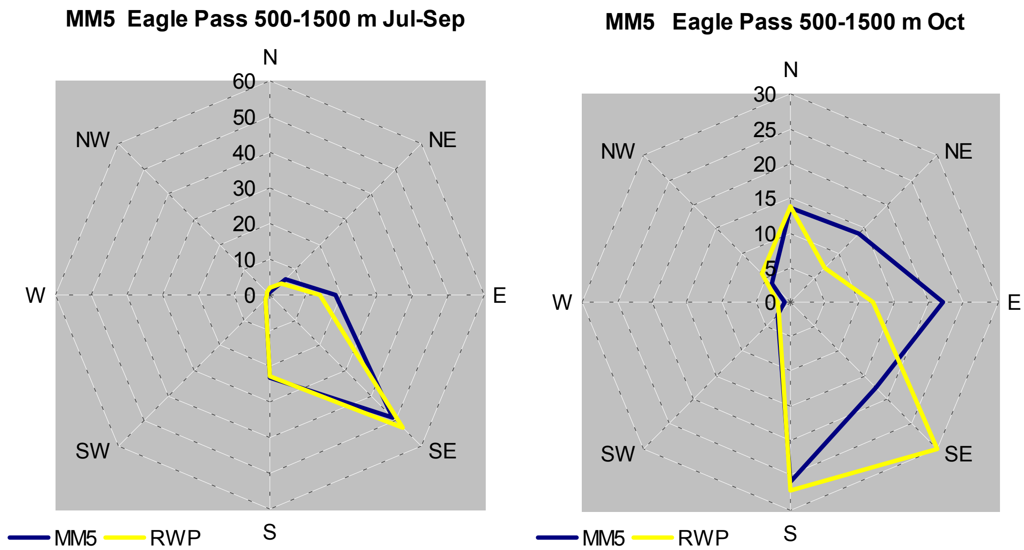


Figure 7. Comparison of MM5 and RWP frequency distributions for the 500 – 1500 m levels at Eagle Pass during July – September and October.

TAGIT Summary

A simple data analysis method called TAGIT (Tracer Aerosol Gradient Interpretive Technique) was used to attribute particulate sulfur and sulfur dioxide at the BRAVO 6 hour sampling sites in and near Big Bend National Park to local and regional sources.

Brief Description of TAGIT

TAGIT is a receptor model that can attribute primary or secondary species associated with the source "tagged" by tracer release or other surrogate. The approach is simple. For each sample period, background concentration of the species, such as particulate sulfur, is determined by averaging the concentrations of the species at nearby sites that do not have elevated tracer concentrations that are significantly above background. This background for each sample period is then subtracted from the concentration of the species of interest at impacted receptor sites for corresponding sample periods. The difference is the concentration attributable to the tagged source.

Approach Used for BRAVO

The initial analysis used gradients in the perfluorocarbon tracer ocPDCH which was released at Eagle Pass, Texas, about 25 km northeast of the Carbon I and II power plants in Coahuila, Mexico. Because the ocPDCH did not correlate well with SO_2 for individual 6-hour sampling periods, it was concluded that perfluorocarbon tracer did not properly represent the location of the emissions from the Carbon plants. This would result in an underestimate of the impacts of these plants to SO_2 and particulate sulfur.

The TAGIT approach was again applied using SO_2 as a tracer for "local" sources (referred to as T AGIT SO2 method). In this approach, one background site - the 6-hour site with lowest SO_2 for each sampling period-was used. This site was then assumed to characterize regional SO2 and particulate sulfur concentrations for the 6-hour period. The differences in SO_2 and particulate sulfur levels between this site and the other sites was then determined to represent the "local" contribution. All data was normalized to the average air density at the main Big Bend National Park monitoring site (BIBE).

Results

Results are summarized in Tables 1-4. Average contributions to particulate sulfur range from about 3% using the ocPDCH tracer (8% when tracer is significantly above background) to about 10% using the SO_2 method (all periods). Because the ocPDCH was not released from the large sources of SO_2 in the area, the TAGIT-SO_2 method is deemed more credible. The SO_2 attribution ranges from 27% when tracer is above background (35% of samples) using the tracer method (not shown in tables) to 75% using the SO_2 method (all periods).
The results strongly suggest that the Carbon power plants were significant contributors to SO_2 concentrations during the four-month BRAVO Study, but contributed a small fraction (10% of less) of the particulate sulfur, on average at the five 6-hour sites in and around Big Bend National Park.

For the TAGIT-SO_2 method, 19% of the local and 86% of the regional sulfur is particulate (the remainder being gaseous in SO_2). Thus, most of the regional SO_2, but relatively little of the local SO_2 has been converted to particulate sulfur. The low fraction of conversion of local SO_2 to particulate sulfur is consistent with the typical 15-18 hour transport time for transport from the vicinity of the Carbon power plants to the 6-hour sites determined using the BRAVO tracer data.

Table 1. Average TAGIT attributed particulate sulfur (ng/m3) at each site for periods with elevated tracer concentrations. Also shown are the average particulate sulfur, percent of sulfur at the sites attributed by TAGIT, and the percent of observations with tracer above background.

	BIBE (n=16)	**FTST (n=55)**	**MARA (n=41)**	**PRSG (n=45)**	**SNVI (n=12)**	**ALL (n=169)**
Average TAGIT attributed S	86±65	66±69	75±37	75±48	189±90	80±26
Average S for TAGIT assessment periods	899	1038	942	954	803	958
% S attributed for impact periods	9.6±7.2	6.4±6.6	8.0±3.9	7.9±5.0	23.5±11.2	8.4±2.7
% of periods with ocPDCH>background	22	50	48	37	16	35

Table 2. Use of TAGIT- SO_2 method for attribution of particulate sulfur.

	BIBE	**FTST**	**MARA**	**PRSG**	**SNVI**	**ALL**
Average attribution (ng/m3)	136±18	38±21	95±21	138±20	42±21	91±9
% of particulate sulfur	14.4±1.9	4.3±2.4	10.1±2.2	14.0±2.0	4.6±2.4	9.8±1.0

Table 3. Use of TAGIT- SO_2 method for attribution of SO_2 sulfur (SO_2/2).

	BIBE	FTST	MARA	PRSG	SNVI	ALL
Average attribution (ng/m3)	273±38	518±40	434±39	531±53	179±29	397±19
% of SO_2 sulfur	68±10	76±6	76±7	79±8	61±10	75±4

Table 4. Use of TAGIT- SO_2 method for attribution of total sulfur

	BIBE	FTST	MARA	PRSG	SNVI	ALL
Average attribution (ng/m3)	408±50	556±51	529±52	669±65	221±41	488±24
% of total sulfur	31±4	36±3	35±3	40±4	19±3	33±2

TASK V: TERRESTRIAL ECOSYSTEMS AND CLIMATE

Evaluation of the Atmospheric, Soil, and Plant Community Parameters that Influence Surface Water Balance and the Relationship to Waste Disposal

Project Personnel: William Albright, Brad Lyles (DRI/DHS); Craig Benson, Preecha Apiwantragoon, Arthur Roesler (Univ. of Wisconsin/Madision); Tarek Abichou (Florida State University)
Task: Terrestrial Ecosystems and Climate
Goal: Improve understanding of the dynamics and interactions between soil, plant communities, atmospheric parameters, and moisture in the near-surface environment that comprises final landfill covers.

Introduction

The U.S. Environmental Protection Agency's (EPA) ACAP program is operating ten monitoring stations to improve understanding of the dynamics and interactions between soil, plant communities, atmospheric parameters, and moisture in the near-surface environment that comprises final landfill covers. The ACAP program was designed to evaluate and compare the performance of alternative earthen final covers (AEFCs) and conventional cover designs and provide measurements that can be compared and contrasted between all covers at the ten ACAP sites.

The Resource Conservation Recovery Act (RCRA) describes the requirements for conventional landfill cover designs and requires demonstrated equivalent performance for alternatives. RCRA Subtitle D recognizes four cover designs that correspond to four configurations for liners placed below the waste. For both liners and conventional covers the design criteria are quantity of material (thickness) and a specified value of a material parameter (saturated hydraulic conductivity). In contrast, AEFC design relies on site-specific characterization of variables (soil, plants, climate) relevant to maintenance of a favorable water balance in the cover.

Although each of the measurements incorporated in the ACAP program has been utilized in other landfill cover evaluation studies (e.g., Khire et al. 1997, 1999, Ward and Gee 1997, Chadwick et al. 1999), ACAP is the first application of these methods in a field-scale, nation-wide, multi-year monitoring program. The objectives of this report are to 1) describe the sites selected for ACAP evaluation studies, 2) describe the variables measured at the sites with respect to method 3) describe the cover designs currently being tested, and 4) provide a summary and preliminary interpretation of field data from the first two years of observation.

Sites Descriptions

The intent of the ACAP program was to locate field-scale study sites in a wide range of the physical environments found within the United States. With the completion of construction in March, 2002 there are ten sites located in eight states across the county. California leads in total number of sites with four (Altamont, Monterey, and Sacramento). Montana (Helena and Polson) has two sites. Oregon (Boardman), Utah (Monticello), Nebraska (Omaha), Iowa (Cedar Rapids) and Georgia (Albany) each host a single site.

Within the research network there is a broad sampling of the environmental factors that influence the performance of final landfill covers. These environmental factors become design parameters when emphasis is shifted from use of a conventional design in favor of a site-specific descriptive design process. The primary factors that influence success of an AEFC design are soil hydrologic parameters and a variety of climatic and plant community characteristics.

Soils: The soil hydrologic parameters most important in the design of covers are water holding capacity and hydraulic conductivity. AEFC designs generally favor soils with higher water holding capacity for their ability to store precipitation within reach of the surface processes of evaporation and transpiration. An exception to this is the use of coarse-grained soils in a fine-over-coarse arrangement to create a capillary break. Conventional designs generally require fine-grain soils to meet the minimum hydraulic conductivity requirement inherent in the RCRA designs. Soils used in the ACAP program for construction of AEFCs range from the clay-rich soil used in an evapotranspiration-type design to sandy gravel used for a capillary break. Fine-grain soils used for construction of conventional covers were available on site at some locations; at others it was imported.

An extensive program of soil sampling was conducted during construction of the test pads. Samples were taken following placement of each soil lift (between 15 cm and 45 cm depth of soil). The sampling schedule consisted of four disturbed samples (5-gal buckets), two Shelby tubes, and two large (15 cm x 15 cm) undisturbed block samples. Disturbed samples were analyzed for grain size and compaction characteristics, the Shelby tube samples and the large undisturbed samples for saturated hydraulic conductivity and unsaturated hydraulic parameters.

Climate: Climatic parameters that influence the performance of landfill covers include annual total precipitation, seasonality of precipitation, and the factors that affect potential evapotranspiration (ET) (solar radiation, wind speed, relative humidity, temperature). A primary consideration in the design of an AEFC is the relative seasonality of precipitation and transpiration. At ACAP sites located in northern states significant precipitation occurs as snow and during cooler months when transpiration is at or near zero. The need to store precipitation in the cover for extended periods of time until the onset of the transpiration season is an important design consideration for AEFCs at such sites. In contrast, mild wet winters and dry summers at the three California sites result in coincidence of precipitation and transpiration during the winter months.

Plants: The ideal plant community for an AEFC takes up water for transpiration throughout the soil profile and throughout the year. Site characteristics limit this function primarily by temperature and seasonality of precipitation. Design plant community characteristics vary widely across the study sites. Some sites have conducted revegetation efforts with annual and perennial grass mixtures; other sites have employed trees and shrubs to provide transpiration. Two sites (Albany and Cedar Rapids) have planted hybrid poplar trees with an understory of grasses.

Publications and Presentations

Albright, W. H., Benson, C. H., Gee, G. W., Abichou T., Roesler, A. C., Rock S. A., 2003. Examining the Alternatives, *Civil Engineering*, May 2003.

Apiwantragoon, P., Benson, C. H., Albright, W. H., 2003. Comparison of water balance predictions made with HYDRUS-2D and field data from the Alternative Cover Assessment Program (ACAP), Modflow '02 Conference.

Albright, W. H., Benson, C. H., 2003. Field Tests and Simulations of Alternative Covers in the Alternative Cover Assessment Program (ACAP). USEPA Phytoremediation Conference, Chicago, IL. March 3-5, 2003.

Benson, C. H., Albright, W. H., 2003. Field Performance of Conventional Covers in the Alternative Cover Assessment Program (ACAP). USEPA Phytoremediation Conference, Chicago, IL. March 3-5, 2003.

Field Methods

The primary features of the ACAP program are the large (10 m x 20 m) pan-type lysimeters (Benson et al. 1999) that allow direct measurement of most variables in the near-surface water budget. The geomembrane is low-density linear polyethylene (LLDPE) and forms the bottom and sides of the lysimeter. Full-scale (in depth) portions of the tested cover designs were constructed in the lysimeters. A layer of geocomposite was placed between the geomembrane and the cover soils to protect the membrane and allow rapid lateral transmission of intercepted water through the drainage collection system. Surface berms delineate the edges of the lysimeter to prevent run-on and collect run-off. Surface slopes of the lysimeters were representative of site conditions and range from 5 to 25 percent. Collection systems made of PVC pipe carry drainage and surface run-off water to redundant measurement systems. Soils within the lysimeters are instrumented at multiple depths for measurement of soil moisture content and matric potential.

The emphasis on measurement in the ACAP program is continuous determination of the components of the water budget in the cover soils. Those components are 1) precipitation, 2) surface flow, 3) soil moisture storage, and 4) deep percolation. ET is estimated by the difference between precipitation and the other components and can be calculated from measured meteorological parameters by the method of Penman (Monteith and Unsworth, 1990). Measurement is taken every 15 minutes of most variables within the program. Data are normally stored on one-hour intervals. At times of intense activity (an intense rain event with high surface runoff, for example), data are stored at time intervals as short as every 15 seconds.

The primary method of measuring deep percolation, lateral flow (interflow), and surface runoff is by dosing siphon. The siphons used in the ACAP program are activated by the addition of 85-100 liters of water to the siphon basins (100 liters corresponds to 0.5 mm of flux distributed aerially across the lysimeter). Siphon activation triggers a float switch to send a signal to the data logger. Basins differ in the amount of water required to activate the siphon and each is individually calibrated. A pressure transducer, located in the bottom of each siphon basin, makes additional verification of siphon events by use of an algorithm in the data logger program that determines the rate and direction of change in the transducer measurements. In each deep percolation basin, where expected flow rates are low, a tipping bucket gauge provides an additional measurement of flux.

Soil moisture storage is determined by integration of point measurements of soil moisture content at multiple depths. Instrument nests are located below three locations on the surface of each lysimeter.

Measured meteorological parameters include precipitation, air temperature, relative humidity, solar radiation, wind speed, and wind direction.
A central instrument station includes the meteorological instruments, data logger, multiplexers, solar panel (at most sites), along with a cellular phone that allows daily remote access to the data.

ACAP Program Hypotheses

At most ACAP sites the primary hypothesis matches the current regulatory requirement for an alternative cover: the performance of the alternative design will equal or exceed that of the appropriate conventional design. In current engineering practice this requirement is confounded by two problems: (1) there are very few field-scale data sets indicating the performance of any type of cover design, conventional or otherwise; and (2) without field-scale performance data, predicted estimates of performance must be made on the basis of: (a) material parameters (i.e. the use of low-permeability clay, which neglects the propensity of clay to form macropores); or (b) numerical simulations which suffer from the lack of the above-mentioned field-scale data. The ACAP program was designed to evaluate and compare the performance of both conventional and alternative cover designs in side-by-side comparison in support of the primary hypothesis of this report. Lysimeter testing of both alternative and conventional covers is under way at eight ACAP sites. The remaining three lysimeter-equipped sites include testing of either a single alternative or multiple alternative designs without testing a conventional design. The performance of each cover will be evaluated on an annual basis for a period of five years. The five year period of the program will allow adequate time for plant communities to mature and for testing to span significant variation in meteorological parameters. The application of this advanced measurement technology over an extended period will provide regulators and design engineers with the knowledge needed to consider alternative designs in a variety of physical environments.

Results

Construction of the ACAP field facilities was completed in the fall of 2000. All data reported here are for time periods through the end of calendar year 2002 unless otherwise noted. The large number of sites (10), test pads (21) and measured variables preclude the possibility of thorough examination of all field data in this report. Cover performance is discussed in this paper from the point of view of the major components of the water balance, precipitation, surface runoff, percolation, and evapotranspiration. Test sections for composite designs also include a measurement of the flow off the geomembrane component of the design, referred to here as "lateral flow".

Conventional covers, composite designs. Cover designs that combine a geomembrane with low-permeability soil (typically compacted clay) or a geosynthetic clay layer (GCL) to form a composite hydraulic barrier are the recommended minimum for modern landfills constructed with similar composite bottom containment (liner) systems. Composite covers are being tested by ACAP at six locations: Monterey and Altamont, CA, Boardman, OR, Polson, MT, Omaha, NE, and Cedar Rapids, IA. The water balance in a composite cover includes not only percolation and surface runoff, but also lateral flow water diverted by the geomembrane component of the cover design.

The composite cover at Boardman recorded no percolation or surface runoff during the monitoring period. Precipitation at Boardman for the two calendar years was 63 and 52 percent of the long-term annual mean during the two monitoring years. A small amount (0.5 mm) of lateral flow was measured. The water content of the 90-cm soil component of the cover above the geomembrane dried through the monitoring period and ET exceeded total precipitation by about 20 percent.

The composite covers at the other semi-arid sites, Altamont and Polson, recorded small amounts (3.1 mm at Altamont, 0.5 mm at Polson) of percolation. Precipitation at Altamont was within ten percent of the mean annual value of 358 mm during both years of monitoring; precipitation at Polson was about 20 percent below the mean of 380 mm both years. Percolation at both sites was associated with heavy precipitation events and was accompanied by surface runoff and lateral flow on the geomembrane component of the cover. Not all surface runoff and lateral flow events were associated with percolation. Surface runoff represented five percent and two percent of the water budget at Altamont and Polson, respectively; lateral flow was less than one percent and three percent. The small amount of percolation at both sites occurred when soil moisture was at low to moderate levels, suggesting that water reached the geomembrane through preferential flow paths.

The composite cover at Omaha recorded a total of 5.5 mm of percolation, most of which occurred in response to a single heavy rain event during a few days in early May of 2001. Surface runoff, at 79 mm, accounted for nearly 8 percent of the 1136 mm of total precipitation. Lateral flow totaled approximately five percent of the water budget. All percolation through the Omaha composite cover was accompanied by surface runoff and lateral flow on the geomembrane; lateral flow and surface flow events were not always accompanied by percolation.

The composite cover at Cedar Rapids recorded 9.5 mm of percolation despite a 199-day interruption in data collection from mid-November of 2000 to early May of 2001. Most of the percolation occurred in June and July of 2002 in response to heavy precipitation events. Lateral and surface flow, while not always accompanied by percolation, accompanied all percolation events. During 2001 and 2002 surface runoff and lateral flow on the geomembrane each accounted for less than five percent of the 1586 mm total precipitation.

Among the composite covers tested, performance of the design at Monterey CA was an outlier, allowing 52 mm of percolation. During each of the two monitoring seasons percolation began when the soil water storage above the membrane reached about 210 mm of water and continued until the soil profile dried following the winter wet season. Percolation at Monterey was episodic and generally coincided with surface flow and lateral flow. Percolation represented six percent of the 819 mm of total precipitation, surface flow nearly twelve percent, and lateral flow over the geomembrane another three percent. During construction the geomembrane in the cover was not covered by geotextile or sand, and soil with cobbles and other debris was placed directly on the membrane. Punctures likely were the result and responsible for the relatively large amount of flux through the cover.

Conventional covers, compacted clay design. Cover designs that use a layer of compacted clay to impede percolation into waste are the recommended minimum design for landfills with low-permeability soil liners or unlined, often older, sites. Two compacted clay covers are being tested at humid locations (Cedar Rapids, IA, and Albany, GA).

Between mid-March 2000 and mid-September 2002 the compacted clay cover at Albany allowed 698 mm of percolation, or nearly one third of the 2215 mm of precipitation during the monitoring period. Precipitation events at Albany were more frequent that at the other sites and soil water storage in the cover fluctuated rapidly in response. Surface runoff accounted for slightly more than ten percent (281 mm) of precipitation. In the period prior to early November of 2000 the cover limited percolation to about nine percent of precipitation (44 mm percolation to 494 mm precipitation) and showed only moderate temporal response to precipitation events. After that date, and following a six-week drought that reduced soil moisture storage to less than 150 mm for the first time, the cover allowed about 38 percent of precipitation to pass as percolation (652 mm percolation to 1721 mm precipitation). Following the drought, precipitation events typically were followed within a few hours by percolation which developed a distinct “stair step” pattern.

Data for the compacted clay cover at Cedar Rapids represent two periods separated by 199 days (October 18, 2001 to May 4, 2002) for which data are not available. In the first twelve-month period, 772 mm of precipitation produced just 3 mm of percolation. Surface runoff during this period was two percent of the water budget, lateral flow over the compacted clay layer less than one percent. Following resumption of data collection, percolation (44 mm) represented about five percent of precipitation (814 mm). Surface runoff totaled nearly five percent of the water budget; three percent was lateral flow over the clay layer. In the later period percolation mirrored precipitation in time and significant periods of percolation occurred at times when soil moisture storage was both relatively high and low. These observations suggest that much of the percolation measured during the later period was associated with preferential flow paths through the clay barrier.

Alternative covers, arid and semi-arid sites. Alternative covers tested at arid and semi-arid sites include monolithic designs at Altamont, and Sacramento, CA, and Boardman, OR, and capillary barrier designs at Polson and Helena MT, and Monticello, UT.
Neither alternative cover at Boardman recorded any percolation or surface runoff during the monitoring period. Precipitation was 64 (2001) and 53 (2002) percent of the 221 mm annual mean value. Vegetation observed on the covers was sparse due to relatively dry conditions. Total evapotranspiration, however, exceeded precipitation and the soil in both covers dried over the monitoring period. Soil water storage (300 mm in the thick cover, 255 mm in the thin cover)

did not approach the maximum storage capacity of 756 mm and 512 mm for the thick and thin covers respectively.

The capillary barrier design at Helena allowed no percolation during the monitoring period. Precipitation during the two full years of data collection was 74 (2001) and 86 (2002) percent of the annual long-term mean value of 305 mm. Surface runoff represented about five percent of the total water budget and water storage in the cover soil varied seasonally between 200 and 300 mm of water compared to the calculated maximum storage capacity of 470 mm. One significant feature of the water budget at Helena was a 10-day surface runoff event in early March 2001 caused by melting snow. Soil water storage increased during this period but the lack of percolation suggests an absence of preferential flow paths.

The capillary barrier cover at Polson recorded two percolation events of 0.05 and 0.4 mm. The first coincided with a precipitation event in late February 2000, the other was the result of snowmelt in early March 2002. Both events included recorded surface runoff and occurred when soil moisture storage was at low to moderate levels. Precipitation during the two full years of data collection was 88 and 89 percent of the annual mean of 345 mm. Soil moisture storage in the cover ranged seasonally between 100 and 250 mm (317 mm calculated maximum storage capacity) with minimum values in late fall and higher values a result of snow melt and spring rain.

The alternative cover at Altamont recorded a total of 1.8 mm of percolation during two full years when precipitation was 107 and 93 percent of the mean annual value of 358 mm. Soil moisture ranged between 175 and 300 mm of water (347 mm calculated maximum storage capacity). Higher values coincided with wet winter weather, lower values with the typically dry summers. The two percolation events at Altamont occurred when soil moisture was rising, but still midway between the two extremes. Both events were accompanied within a few days by surface runoff, which accounted for about eight percent of the total water budget.

The large lysimeter at Monticello has recorded slightly less than 0.5 mm of flux through the multi-layer cover. Most of the drainage occurred in a 2-week period in late February 2001 that included heavy precipitation, surface flow and a peak in soil water storage of about 305 mm (668 mm calculated maximum soil water storage capacity). Even though water storage in the cover remained high for another two months, no additional percolation occurred. Precipitation during the two full years of monitoring at Monticello was 67 and 71 percent of the annual mean of 385 mm. Surface runoff accounted for eight percent of the total water budget. Soil moisture recorded seasonal low values in January and early February and higher values in spring of 2001 and in response to monsoon rains in late summer of both years.

Test sections for the two alternative designs at Sacramento were the first to be constructed by ACAP and have more than three years of data. That relatively long period of evaluation gives some indication of the annual variation in response of the cover to the imposed environmental conditions. Precipitation is seasonal at Sacramento with wet cool winters and hot dry summers. Precipitation during the three years (July through June) totaled 119, 82, and 65 percent of the mean annual of 434 mm. Percolation for those periods was 0, 2, and 130 mm for the thin cover; 0, 0, and 8.5 mm for the thick cover. Surface runoff totaled ten and six percent for the thin and thick covers respectively. The amount of water stored in the two soil profiles varied seasonally with precipitation and evapotranspiration, and significantly for cover performance, differed between the summers of 2000 and 2001. During the winter of 1999-2000, moisture content of the soil in both covers increased from winter precipitation (375 mm for the thin cover, 565 mm for the thick cover) and then decreased through the following summer to values similar to those measured following construction the previous summer (165 mm for the thin cover, 375 mm for the thick cover). Even though the precipitation during the following winter (2000-01) was about one-third less than the winter of 1999-2000 the soil moisture reached higher levels in both covers (50 mm more for the thin cover, 60 mm more for the thick cover). The following summer (2001) soil moisture (310 mm for the thin cover, 575 mm for the thick cover) remained significantly higher in both covers than during the previous two summers. When precipitation resumed in the fall of 2001 there was less available storage capacity and soil moisture contents in both profiles reached peak values (930 mm in the thick cover, 440 mm for the thin cover) that exceeded values required for percolation. In the thin cover, the critical value for soil water storage that marked the onset and cessation of percolation was about 390 mm compared to the calculated maximum storage capacity of 295 mm. For the thick cover the critical value was between 750-800 mm (calculated maximum storage capacity of 820 mm). During the summer of 2002 soil water storage in the thin cover returned to values much lower (180 mm) than during the previous summer (310 mm). Soil water stored in the thick cover (515 mm) did not follow that pattern and showed only moderate decrease below the level of the previous summer (575 mm).

Alternative covers, humid sites. Alternative covers tested at humid sites include monolithic designs at Cedar Rapids, IA, and Albany, GA and capillary barrier designs at Monterey, CA, and Omaha, NE.

Percolation through the alternative cover at Monterey totaled six percent of precipitation, which was 62 and 72 percent of the long-term mean annual value (466 mm) during the two full years of monitoring. There was no recorded surface flow. Both soil water storage and drainage responded directly to the seasonal precipitation pattern. During both years of monitoring soil water storage increased in response to the onset of precipitation in the fall and drainage occurred when soil water storage exceeded 275-300 mm of water (calculated maximum soil moisture storage capacity of 413 mm). Soil water storage decreased during each successive summer of observation (250 mm, 215 mm, and 200 mm) reflecting increasing ability of evapotranspiration processes to dry the soil and provide additional storage capacity.

Both capillary barrier designs at Omaha allowed significant percolation during the first full year of monitoring but showed improvement in performance during the second year. Precipitation during the first two years (October through September) of monitoring was 80 and 58 percent of the long-term annual mean value of 760 mm. The peak in soil water storage occurred during the spring of 2001 and coincided with percolation through both covers. Most of the percolation through the thick cover occurred during a 20-day period in May 2001 when soil water storage was in excess of 325 mm. Percolation through the thin alternative showed a similar response during that period when heavy rain caused soil water storage to rise above about 250 mm of water. The calculated maximum soil moisture storage for the thick and thin covers is 384 mm and 274 mm, respectively. Soil water storage has not exceeded 260 mm and 240 mm in the thick and thin covers respectively since June 2001. Surface runoff totaled seven and five percent of the total water budget for the thin and thick covers respectively and occurred primarily as a result of the storms in May 2001 before the vegetation community matured.

Results from the Cedar Rapids alternative cover are separated into two distinct periods by a 199-day gap in the data. During the first 12-month (October 2000 through October 2001) period percolation totaled 150 mm while precipitation was 84 percent of the 914 mm long-term annual mean value. During the second, 8-month period (from May to December 2002 precipitation of 813 mm resulted in 57 mm of percolation. Surface runoff accounted for just 4 percent of the total water budget. Percolation began in mid-March of 2001 during a period of light precipitation and increased when the soil water storage exceeded 400 mm of water (calculated maximum soil moisture storage capacity is 462 mm). Percolation continued, but at a lower rate, as the rate of precipitation decreased during the summer months even though soil moisture storage remained high (450-500 mm of water). Soil moisture storage decreased during the fall of 200 and early winter to about 265 mm of water, increased to 450-500 mm during the spring of 2001 and remained at that level through the summer. During the second data collection period most of the recorded percolation occurred during a 10-day period in early June 2002 that coincided with heavy (140 mm in 16 days) precipitation and surface runoff. Soil moisture storage during this period was above 500 mm of water.

Percolation through the alternative cover at Albany occurred during three distinct periods. During the first six months of data collection percolation was 164 mm, or 25 percent of the 660 mm of precipitation. This was followed by 22 months during which percolation (21 mm) was less than 2 percent of the 1530 mm of recorded precipitation. During the last five months of 2002 the percolation (216 mm) increased and represented 30 percent of the 717 mm of precipitation. During the two full (calendar) years of observation precipitation was 65 and 97 percent of the long-term annual mean value. Surface runoff represented less than one percent of the water budget. Wet soil was used to construct the cover and free drainage was recorded at the onset of monitoring. With no plants to provide transpiration, frequent precipitation events were reflected in the drainage recorded during the first six months. During that time the soil water storage ranged in value between 350 mm and 425 mm of water (calculated maximum soil moisture storage capacity is 478 mm). A seven-week drought in fall 2000 decreased soil water storage value to 285 mm of water and marked the beginning of the 22-month period during which little drainage occurred and soil water storage values fluctuated between and 245 mm and 360 mm of water. The final three of these 22 months were a period of relatively low precipitation and brought soil water storage values to the low point of the monitoring period. Drainage resumed with precipitation even though soil water storage values remained low, between 245 and 310 mm of water. Increased temporal response of drainage to precipitation events during this last 5 months of monitoring suggesting development of preferential flow paths through the soil profile.

Discussion

Composite designs. Except for the design at Monterey, the composite covers limited percolation to one percent or less of precipitation at all sites. Lateral flow accounted for less than four percent of precipitation at all sites. Percolation through the composite covers was closely linked in time to precipitation events, especially those resulting in surface flow, and in most case was preceded or accompanied by lateral flow over the geomembrane component of the cover. Correlation with occurrence of lateral flow over the geomembrane was not surprising given the relatively thin layers of soil that cover the membrane. Four of the five composite designs have overlying cover thickness of 60 cm or less and the maximum thickness is 90 cm. The coincidence of percolation and lateral flow shows that lateral flow and percolation quickly followed heavy precipitation at Cedar Rapids in early June and early July 2002. Heavy precipitation in early May of 2001 at Omaha caused a similar response and most of the recorded percolation through that cover. The single occurrence of percolation through the composite cover at Polson followed a rainstorm in July of 2001. All of the percolation through the composite cover at Altamont occurred during a wet 2-week period in December 2002 that also included lateral flow. At Monterey percolation through the cover was accompanied by lateral flow in two of the three wet seasons observed during the monitoring period.

Performance of the composite cover at Monterey illustrates the importance of careful handling and construction methods required by the geomembrane component of such covers. The soil layer immediately above the geomembrane was placed at moderate density (85% of standard Proctor by tracked equipment) to minimize pressure on the geomembrane. Careful visual inspection was made of the soil as it was placed on the geomembrane and rocks and other debris were removed. Despite these procedures 52 mm of water (6 percent of the 819 mm of precipitation) passed through the geomembrane as percolation.

Compacted clay designs. There was a notable change in performance in the compacted clay covers at both Cedar Rapids and Albany several months following construction. The amount of drainage and the temporal response to precipitation events increased at both sites. At Albany the change in performance followed a 6-week period of drought during which the soil profile dried for the first time following construction. Soil water storage decreased during the drought and desiccation cracks were observed. When precipitation resumed in mid-November the response of the cover to precipitation events was altered and precipitation events were often followed within hours by increased percolation rates. The average percolation rate did not return to the pre-drought status indicating that desiccation cracks in the clay barrier did not seal when soil moisture increased. It is assumed that much of the flux that occurred following the drought was the result of preferential flow paths formed by desiccation cracks. At Cedar Rapids the exact time and related conditions are obscured by a gap in the data but the late-time data clearly represent a period of altered performance. At Cedar Rapids three periods of heavy precipitation during the spring, summer, and fall of 2002 are matched in time by percolation events through the compacted clay cover.

Two aspects of altered performance are apparent. First, expressed as a percentage of precipitation, percolation in each increased by a factor of 4-10. At Albany the increase was from 9 to 36 percent; at Cedar Rapids the increase was from <1 percent to 6 percent. Second, there was increased temporal response in percolation to precipitation events at both sites. The early-time data show little temporal response to precipitation, percolation during the later period developed the characteristic "stair-step" pattern with increased rates of percolation quickly following large precipitation events that were often accompanied by surface runoff.

Alternative designs, arid and semi-arid locations. With the exception of the two covers at Sacramento, the alternative covers located in arid and semi-arid locations limited percolation rates to less than 2 mm/year. Three covers, two at Boardman and one at Helena recorded no percolation. Relatively dry conditions prevailed in the western US during the monitoring period and, except for Altamont, all of the sites recorded annual precipitation totals less than the long-term mean annual values. Surface runoff accounted for no more than 11 percent, in most cases less than 5 percent, of the water budget for any individual year at any site.

Data show that percolation through alternatives at arid and semi-arid sites occurred in response to two general types of site conditions. Some drainage occurred when the water storage in the cover exceeded a certain quantity. Both alternative covers at Sacramento began to drain when the soil moisture stored in the cover reached a certain point (390 mm for the thin cover, 750-800 mm for the thick cover) and ceased when the soil moisture dropped below that point. These figures approximate the calculated maximum soil moisture storage capacities of 290 and 820 mm for the thin and thick covers, respectively. These data support current design procedures that are based on assumptions that some maximum storage capacity must be exceeded prior to significant drainage.

Drainage at some sites occurred when soil moisture storage values were well below those at which percolation would be predicted but coincided with heavy precipitation and surface runoff events. Most drainage at Altamont, and Monticello occurred when soil moisture storage values were low to moderate but increasing due to seasonal precipitation; the single percolation event at Polson was in July when soil moisture values were near a seasonal low point. Percolation under these circumstances suggest either the presence of preferential flow or the effect of localized ponding on the test sections that may not be detected by the soil moisture instruments.

Soil moisture storage values at Altamont, Helena, Boardman, Polson, and Monticello remained well below the calculated maximum storage values throughout the monitoring period. As mentioned above, soil moisture values at Sacramento exceeded maximum storage capacity during one year and significant drainage resulted. The soil moisture storage data for the capillary barrier design at Polson illustrate the effectiveness of that feature in limiting percolation. The field capacity of the fine soil layers without the underlying coarse layer is 189 mm of water, a value exceeded by a wide margin each season of monitoring (250 mm in 2000, 225 mm in 2001, and 230 mm in 2002). The presence of the capillary break increased the storage capacity to 317 mm as determined by the method of Khire et al. (2000). Most of the increase in storage capacity was realized in the sandy silt layer immediately over the coarse layer.

Alternative designs, humid locations.

Alternative covers at the humid sites allowed the most total percolation expressed both as flux and as a percentage of precipitation. The monolithic design at Albany GA recorded more percolation than any other alternative or prescriptive design with a 32-month total of 401 mm, or about 14 percent of the total water budget at the site. Annual precipitation totals during the monitoring period for all the sites were equal to or less than the long-term mean annual figures. Surface runoff totaled no more than 10 percent of the water budget for any of the covers.

Percolation through alternative covers at humid locations occurred both as a result of exceeding the storage capacity of the soil layers and in response to heavy precipitation events regardless of soil moisture storage status. Percolation at Albany, for example, was closely tied in time to precipitation events, occurred as short duration events, and occurred at times when the quantity of soil moisture stored in the cover was both high and low. In contrast, almost all percolation through the two capillary barrier designs at Omaha was in response to soil moisture storage values that exceeded the calculated storage capacities of the covers. Percolation at Monterey followed the pattern of the Omaha covers with the exception that the onset of flux occurred when soil moisture storage values exceeded about 300 mm, well short of the field capacity of 413 mm.

The data from each of the alternative covers located at humid sites indicate long-term changes in the soil and plant components of the cover systems that may prove important to future design efforts. The effect of both plant community maturity and short-term pedogenesis are suggested in the data from Albany. At Albany three distinct hydrologic regimes are evident: (1) prior to the development of sufficient transpiration capacity, an initial 6-month period characterized by high percolation rates and high soil water storage values, (2) a 21-month period of little percolation preceded by a 6-week drought and characterized by rapid development of the poplar trees that dried the soil profile and, (3) a final period, initiated by a drought that dried the soil profile to the lowest recorded levels, characterized by percolation rates equal to those recorded during the first 6 months and increased temporal response of percolation to precipitation events. A similar development was noted in the compacted clay, conventional design following a drought five months into the monitoring period. The longer period of time required to develop the temporal response to precipitation is probably due to the increased depth of soil in the alternative cover.

Data from the alternative designs at Omaha and Monterey also show the effect of maturity in the plant community on the water balance of the covers. High percolation rates through both covers at Omaha the first spring following construction were not observed the second year of monitoring. Less precipitation occurred the second year but analysis of the water budget data shows that increased transpiration capacity by a more mature plant community was partly responsible for preventing percolation the second year. Construction at Omaha was completed in the fall of 2000 and the plant community had little chance to become established prior to winter weather. During the critical spring months (March 1 through June 1) evapotranspiration was 58 mm and 45 mm from the thin and thick covers respectively. Soil water storage increased in both covers during that period but the increased storage was not sufficient to prevent percolation. During the same months the following year evapotranspiration was 124 mm in both covers and soil water storage showed only a slight increase. The increase in evapotranspiration of 65-75 mm during the spring months helped maintain low soil moisture storage values and reduced percolation to zero in the thick design and 3 mm in the thin cover during the spring of 2002. Performance of the alternative cover at Monterey also indicates the importance of plant community maturity. The quantity of moisture storage in the soil profile at the beginning of the wet winter months decreased each year of monitoring, but not sufficiently to prevent considerable percolation during the wet winter months. Percolation began each year when soil moisture storage reached approximately 300 mm of water. Critical to the function of the cover was the quantity of moisture stored in the soil profile at the end of the dry summer period and prior to the onset of winter precipitation. That value decreased each year of monitoring from 250 mm during the fall of 2000 to 215 mm (fall of 2001) and 200 mm (fall of 2002). The steady decrease in residual moisture stored at the beginning of the wet winter season provided additional storage capacity and does give some indication of the importance of plant community maturity for proper function of ET-type covers.

Conclusions

Data from the test sections show that, when properly constructed, composite covers (i.e., covers consisting of compacted clay or a geosynthetic clay liner overlain by a geomembrane) performed quite well during the two-year observation period. The composite cover at Monterey was an exception and transmitted about 35 mm of percolation (about 18 mm/yr), probably due to damage to the geomembrane during construction. Composite covers at the arid and semi-arid sites limited total flux to less than 2 mm (>1 mm/yr); in more humid sites flux totaled less than 6 mm (>3 mm/yr). Data from the test sections where compacted clay designs were tested at humid sites indicate that the compacted clay barriers in those covers can transmit large quantities of water, probably as a result of desiccation cracking.

Data from the test sections show that, with the exception of the thin alternative cover at Sacramento, alternative covers in arid and semi-arid locations transmitted significantly less percolation than those in more humid locations. Except for the covers at Sacramento all of the covers tested in arid and semi-arid locations transmitted less than 2 mm of percolation during the two-year evaluation period (<1 mm/yr). Percolation through the alternative designs at the more humid sites ranged from 56 to 190 mm for the evaluation period. These overall figures can be misleading, however, as there were significant differences in the performance of some of the alternative covers during each of the two years. The alternative covers at Albany and Omaha allowed most of the total percolation in the first year of observation. At these sites the improved performance was probably a result of increased transpiration due to increased maturity of the vegetation during the second year.

Summary

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